DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS
MISSISSIPPI RIVER COMMISSION

WAVE AND SURGE ACTION
POINT FERMIN NAVAL SUPPLY DEPOT
SAN PEDRO, CALIFORNIA

MODEL INVESTIGATION

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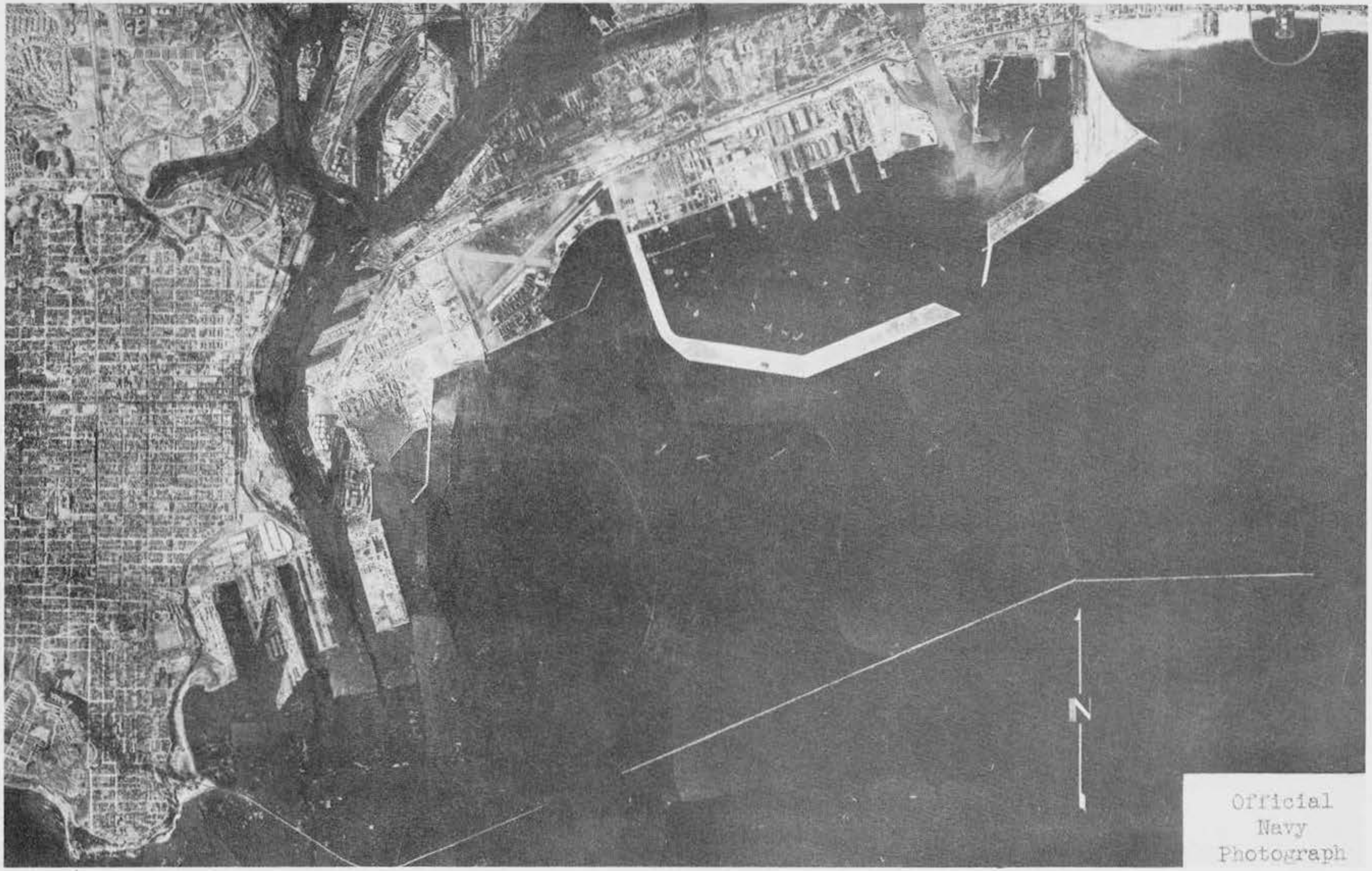

Harbors, San Pedro to Long Beach, California -- October 1945

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WAVE AND SURGE ACTION

POINT FERMIN NAVAL SUPPLY DEPOT

SAN PEDRO, CALIFORNIA

Model Investigation

SYNOPSIS

The model study reported herein was conducted intermittently during the period April 1945 to April 1946 at the Waterways Experiment Station for the Bureau of Yards and Docks, Navy Department. The Bureau was considering the possibilities of constructing a Naval Supply Depot in San Pedro Bay immediately northeast of Point Fermin and east of the City of San Pedro, California. It was proposed that the bay area adjacent to the beach be filled by dredging and a marginal wharf provided on the east side of the fill.

It was known from earlier prototype investigations and model studies* of wave and surge action in that vicinity that long- and short-period waves occurred in San Pedro Bay. It had been found that these waves made loading and unloading operations of ships moored at unprotected piers and wharfs very difficult and, at times, caused damage to ships and fender systems. In anticipation of similar difficulties at the proposed Naval Supply Depot, it was decided to perform prototype and model investigations of the proposed works and harbor area. The prototype wave investigation was carried out to determine the type, magnitude, and frequency of occurrence of the waves which exist in the problem area;

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* See Experiment Station TM No. 2-237, "Model Study of Wave and Surge Action, Terminal Island, San Pedro, Calif.", dated Sept. 1947.

the model study was performed to determine whether it would be hazardous to moor ships along the proposed supply depot wharf under wave conditions as established by the prototype investigation.

Two plans, a comprehensive development and an initial development of the proposed depot, were tested on an existing model of pertinent portions of San Pedro Bay. This model was of concrete construction with scale ratios of 1:60, vertically, and 1:300, horizontally.

It was concluded from prototype wave analysis and model test results that:

a. The outer breakwater system in San Pedro Bay would provide sufficient protection to the proposed supply depot from short-period (5-20 seconds) waves.

b. Undesirable surge conditions would obtain at the supply depot wharf which would require modification of original plans should these surges be considered intolerable.

PART I: INTRODUCTION

The Problem Area

1. The general area with which the model study was concerned is that portion of Los Angeles outer harbor at San Pedro Bay (frontispiece and plate 1) located immediately northeast of Point Fermin and east of San Pedro, California. The site proposed for the supply depot is bounded on the west by the shore line, on the south by the San Pedro breakwater, on the east by the southerly projection of the wharf line on the west side of West Channel, and on the north by the southern boundary of the Army Reservation. The area studied in the model also included West Channel, Watchorn Basin, East Channel, and the outer harbor area west of a line extending from the west navigation opening in the outer breakwater to Reservation Point.

2. The area on which construction of the Naval Supply Depot was contemplated consists of a crescent-shaped portion of San Pedro Bay about 127 acres in size, protected from all but southeasterly storm waves by the San Pedro breakwater. The depth of water varies from zero on the shoreward sides to about 15 ft on the harbor side. In its present condition the shore-line slopes make good spending beaches for those short-period waves which enter the outer harbor through the west navigation opening in the outer breakwater system.

Wave analysis

3. At the beginning of this investigation very little factual or conclusive data were available concerning wave and surge action in the

problem area; however, considerable general information was available relative to the San Pedro Bay area as a whole. The late Mr. D. E. Hughes, engineer in the Los Angeles District Office, CE, presented a very good discussion of the surge problem in an informal letter dated 28 April 1924, which was found in the files of the Los Angeles District Office. Extracts from this letter are presented as an appendix to this report. The U. S. Coast and Geodetic Survey made a comprehensive and valuable study of wave and surge conditions in the harbors of San Pedro Bay in 1935 and 1936, a report of which was published under the title "Los Angeles and Long Beach Harbors -- Tide and Current Survey of 1935-36". Also, rather exhaustive studies of wave and surge action as related to the movements of ships moored at piers at the U. S. Naval Base, Terminal Island (San Pedro), California, were made by the Experiment Station and by the California Institute of Technology in 1944*.

4. Data obtained from the above-mentioned investigations indicated that waves of the following type occur in the harbor areas: (a) local wind waves of from 3- to 9-second period; (b) distant storm waves of from 12- to 18-second period; and (c) long-period waves, propagated from an undetermined origin, ranging in period from less than 1 minute to about 1 hour. The largest local storm waves were found to approach the outer breakwater system usually from about the southeast direction. The distant storm waves usually were propagated from about the southwest

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* See Experiment Station TM No. 2-237, "Model Study of Wave and Surge Action, Terminal Island, San Pedro, Calif.", dated Sept. 1947; and report, "Wave and Surge Study for the Naval Operating Base, Terminal Island, Calif." by the Hydraulic Structures Laboratory, The California Institute of Technology, Pasadena, Calif., dated Jan. 1945.

direction. Of the long-period waves, those with periods of from 2-3 minutes, 6-15 minutes, about 30 minutes, and about 1 hour were found to occur with more regularity than waves of other periods. It was determined previously during the Terminal Island investigations that waves of 2- to 3-minute periods caused more damage to ships at piers and wharfs than waves of any other period which occurred in that area.

5. In order to obtain more complete data pertaining to the characteristics of waves which occur in the Point Fermin problem area, wave-recording gages were installed in the northern ends of West and East Channels. Also, the existing wave-recording gage on Pier 2 at the Terminal Island Naval Base was continued in operation in order that comparisons could be made of waves in West and East Channels with those occurring simultaneously inside the mole-protected Navy Harbor at Terminal Island.

6. An analysis of the marigrams obtained was made for waves which occurred between 13 October 1945 and 13 April 1946. (Marigrams recorded during the winter months were chosen for analysis because it had been found previously that wave action usually increased during this period of the year.) The method of analyzing wave marigrams was the same as that used in the Terminal Island investigation and described in the report on that study dated September 1947. Plates 3-5 present in the form of graphs prototype wave data for comparison with data obtained in the model study. Results of the prototype wave investigation are presented in Part III of this report.

Development plans

7. The complete Naval Supply Depot at Point Fermin, as proposed by the ultimate comprehensive plan (plan 1), would occupy an area of about

175 acres, utilizing a portion of the Army Reservation located along the northwestern side of West Channel. This plan (plate 2) consisted of filling by dredged material to an elevation of about +15 ft the beach area behind the established wharf line on the west side of West Channel in the outer Los Angeles Harbor. The filled area, covering an area of about 127 acres with an average depth below mllw of about 12 ft, would be protected from wave action by riprap placed on a slope of 1:1-1/2 with the toe of the slope immediately inside the face of the marginal wharf line. A pile-supported wharf about 60 to 70 ft in width would be constructed along the riprap-protected slope. The length of the wharf would be about 5400 ft measured from the north end of West Channel.

8. The initial development of the comprehensive plan (plan 1A) contemplated the use of a portion of the Army Reservation located immediately to the north of the proposed supply depot. The supply depot, constructed to this initial plan, would occupy an area of about 78 acres, 28 acres of which would be beach area filled to an elevation of about 15 ft above mllw. The length of the marginal wharf measured from the north end of West Channel would be approximately 3075 ft.

9. The first alternate initial development of the comprehensive plan (plan 2) consisted of a base area of about 85 acres, 64 acres of which would be an area filled to an elevation of about 15 ft above mllw. This development would not utilize any portion of the adjacent Army Reservation. The marginal wharf, about 3900 ft in length, would extend from the north end of West Channel to the south end of the supply depot fill, as did the wharves of the other contemplated plans. An extension of this wharf along the line of the comprehensive plan, together with the

fill behind the wharf, but omitting the building program of the comprehensive plan (other than that proposed for the alternate initial development), was also contemplated (plan 2A).

The Model Study

10. The Chief of the Bureau of Yards and Docks, Navy Department, Washington, D. C., in a letter dated 17 March 1945, to the Director, Waterways Experiment Station, CE, Vicksburg, Mississippi, requested that tests be conducted on the existing Terminal Island model* to investigate wave and surge conditions at the proposed Naval Supply Depot, Point Fermin, outer Los Angeles Harbor, California. Initial authorization for the Experiment Station to construct and operate the Terminal Island model for the Bureau of Yards and Docks was granted by the Chief of Engineers in a teletype dated 26 July 1943, to the President, Mississippi River Commission, CE, Vicksburg, Mississippi.

11. Liaison was maintained between the Bureau of Yards and Docks and the Experiment Station by means of progress reports and conferences. The conferences were held at the Experiment Station with Messrs. Harris Epstein and N. M. Brown, Engineers, representing the Bureau of Yards and Docks. Engineers of the Experiment Station became acquainted with the prototype problem area during visits to the West Coast in connection with the Terminal Island model study. The Public Works Officer, U. S. Naval Base, Terminal Island (San Pedro), California, furnished the prototype

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* Experiment Station report referred to in footnote on page 4.

wave marigrams from which the prototype wave data were obtained for use in this investigation.

12. The prototype wave analysis and the model study were accomplished in the Hydraulics Division of the Waterways Experiment Station. Engineers actively connected with the investigation were Messrs. F. R. Brown, R. Y. Hudson, and J. B. Clark. This report was prepared by Mr. Hudson.

Use of Terms

13. All quantities, both model and prototype, are expressed in this report in terms of prototype equivalents, except where otherwise stated. For purposes of clarity, various terms used throughout the report are defined below:

Depth, elevation. All depths and elevations specified herein are referred to mllw (mean lower low water) in San Pedro Bay.

Wave length. Wave length is the horizontal distance in feet from crest to crest of two successive waves.

Wave height. Wave height is the vertical distance in feet from trough to crest of a wave.

Wave period. Wave period is the time in seconds or minutes between the passage of two successive wave crests by any given point; that is, the time in which a wave travels one wave length.

Short-period waves, long-period waves, surge. Short-period waves (used herein to indicate waves with periods up to about 20 seconds) cause a moored or anchored ship to roll, pitch, and heave. Long-period waves (used herein to indicate waves with periods of about 1 minute or more) cause a ship to execute relatively slow but forceful to-and-fro horizontal movements, usually with scarcely perceptible vertical movements. These latter long-period ship motions, together with the movements of water which cause them, are referred to in this

report as "surge". Waves are classified herein under the arbitrary criterion that short-period waves are those that can be seen on the surface of the water, and long-period waves are those that cannot be detected by eye on the water surface. Using this method of classification, waves with periods of about 30-50 seconds are intermediate, their classification depending on height.

Nodal area. Nodal areas in a harbor are areas in which the vertical amplitude of waves is minimum and the horizontal amplitude is maximum.

Loop area. Loop areas in a harbor are areas in which the vertical amplitude of waves is maximum and the horizontal amplitude is minimum.

Mode of oscillation. The mode of oscillation is the over-all wave pattern, as determined by the positions of the nodal and loop areas, of long-period waves oscillating in a harbor.

Spending beach. A spending beach is a gently sloping beach upon which short-period waves break, thereby expending their energy by turbulence.

Tsunami. A tsunami is a long-period gravity wave in the ocean caused by a sudden large displacement of the sea bottom or shores.

Base test. The term "base test" is used to denote one of several tests conducted, usually at the beginning of a model study, with existing prototype conditions simulated in a model. Prototype elements used to represent base-test conditions are those elements existing in the problem area prior to the beginning of a model study.

PART II: THE MODEL

Description

14. The Point Fermin model study was conducted on an existing model which had been used for the study of similar problems at Terminal Island. The model was of concrete construction reproducing to a horizontal scale of 1:300 and a vertical scale of 1:60 the whole of Terminal Island, all of the coast line from Point Fermin to Anaheim Bay, the Los Angeles inner and outer harbors, the Long Beach inner and outer harbors, Cerritos Channel, all of San Pedro Bay, the San Pedro breakwater, the east detached breakwater, and that portion of the surrounding area of the Pacific Ocean bounded on the west by Point Fermin, on the south by latitude 33° 40' N, and on the east by Anaheim Bay. Figure 1 is a general view of the Point

Fig. 1. Point Fermin model area

Fermin model area and plate 1 shows the prototype area reproduced by the Terminal Island model.

15. In the model, side slopes of all shore line structures, breakwaters, moles, and other reflecting surfaces were constructed using the natural, undistorted, prototype side slopes in order to reproduce accurately the wave reflection and absorption characteristics of prototype structures. Also, the permeability characteristics of the moles, breakwaters and piers were reproduced in the model.

16. Movable wave machines of the plunger type were used to generate both short- and long-period waves. Electrical wave-height measuring and recording devices were used to obtain records of wave heights over the problem area. Figures 2, 3, and 4 show, respectively, the wave-height gage, recording oscillograph, and wave machines.

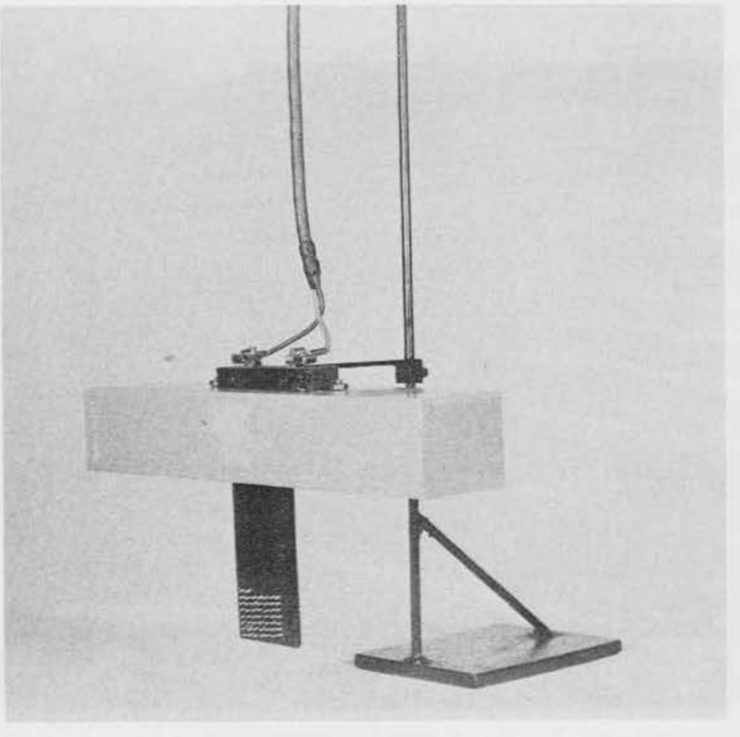

Fig. 2. Wave-height measuring device

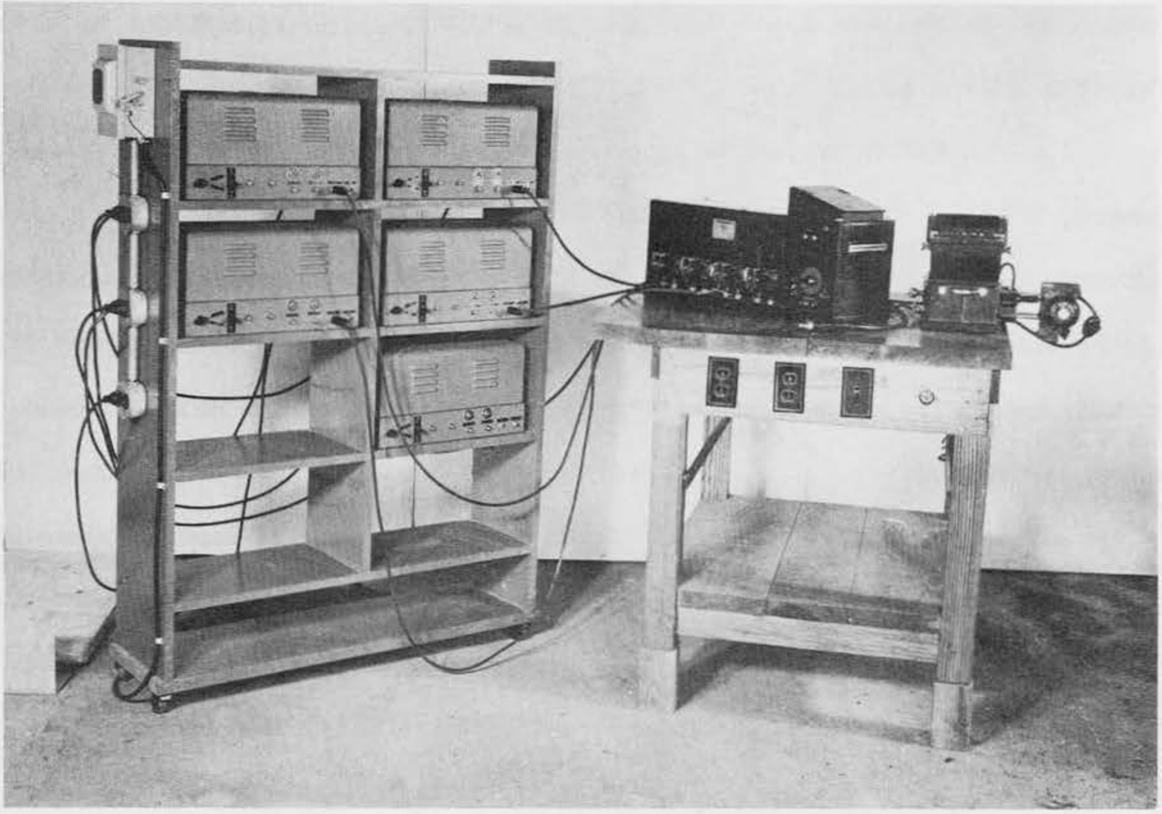

Fig. 3. Wave-height recording apparatus

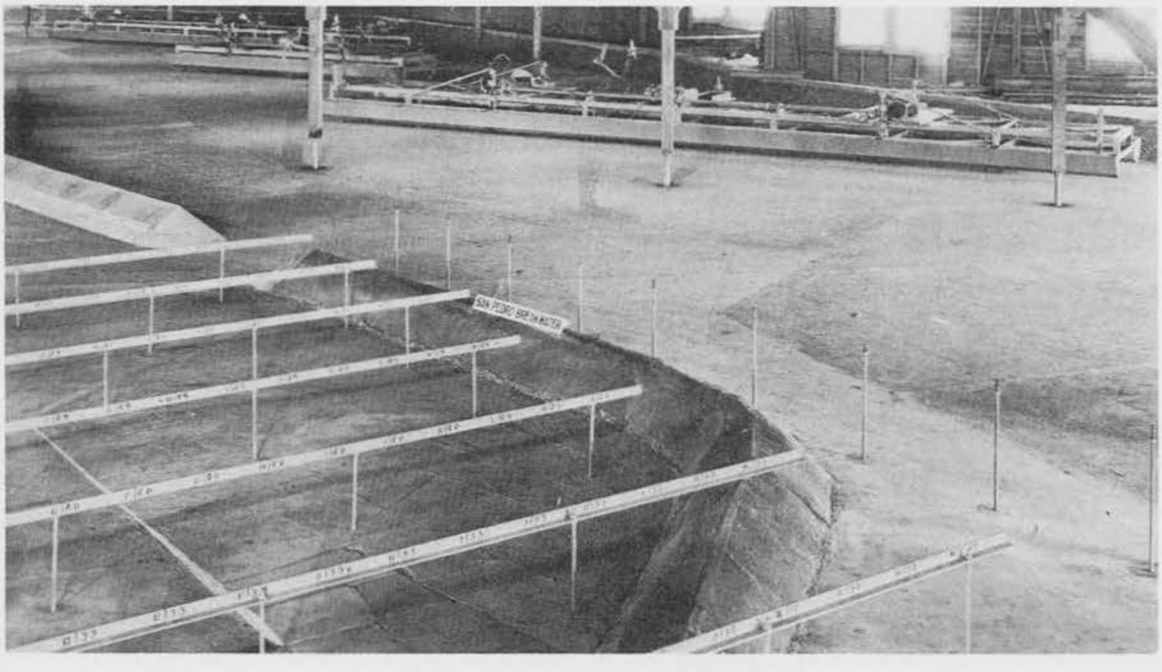

Fig. 4. Wave machines

Testing Procedure

17. Fifteen-second and 2.5-minute waves were selected for study because it had been found in the Terminal Island investigation that waves of these periods occurred quite frequently and were the principal cause of troublesome and damaging ship movements at the Navy piers in that area. The most critical waves which can obtain in a harbor are those whose periods are the same as the fundamental oscillating period (or one of its harmonics) of the harbor basin. This condition is called resonance. The resonant periods of the Point Fermin problem area were determined on the model by performing frequency-response tests. Results of the frequency-response tests were then compared with results of the prototype wave analysis to ascertain the existence of resonant-period waves. In this manner critical waves in the prototype (those occurring with sufficient frequency and magnitude to warrant concern) were determined.

18. Three types of tests were performed: (a) tests using 15-second waves; (b) tests using 2.5-minute surge waves; and (c) frequency-response tests. For the 15-second and 2.5-minute wave tests, waves were generated separately from the south-22-1/2-deg-west, south, and southeast directions and wave heights were measured at 1-ft intervals (model dimensions) over the problem area. Results of these tests were plotted on data sheets and contoured to show wave heights and patterns for base-test conditions and conditions for each proposed construction plan. The frequency-response tests were conducted with a wave machine located at the west navigation opening in the outer breakwater and aligned so that the longitudinal axis of the generated waves would be parallel with the

proposed wharf and the East and West Channels. Waves were generated using periods ranging from about 12 seconds to 14 minutes, and wave heights were measured at the west navigation opening and at the north ends of East and West Channels and Watchorn Basin. From these data the periods at which resonance obtained for each of these oscillating bodies of water in the problem area were determined for base-test conditions and with each of the proposed plans of construction installed in the model. For wave periods of 2, 3, 4, 6, 8, 10, 12, and 14 minutes, using base-test conditions, complete mode-of-oscillation data were obtained by measuring wave heights at 1-ft intervals (model dimensions) over the problem area. Wave heights were plotted on data sheets and contoured to show the modes of oscillation for each of the wave periods listed above.

19. The 15-second waves were 12 ft in height and 600 ft in length, measured outside the outer breakwater system. The 2.5-minute waves were about three feet in height and nearly 6,000 ft in length, measured outside the outer breakwater. The heights of waves generated for the frequency-response tests varied for the different wave periods. A still-water level of 3 ft mllw, approximately equivalent to mean-tide conditions, was used for all tests.

Plans Tested in the Model

20. Base-test conditions (figure 1) and plans 1 and 2 were tested in the model. Because of the similarity of plans 1 and 2A and plans 1A and 2 (plate 2), plans 1A and 2A were not tested. The results of tests of plans 1 and 2 are considered generally applicable to plans 2A and 1A, respectively.

PART III: RESULTS OF PROTOTYPE WAVE STUDY

21. Results of the prototype wave-record analysis are presented in graphical form on plates 3-5. Plate 3 shows wave periods, together with the approximate percentage of time each period wave occurred at gaging stations 9, 10, and 11 during the analysis period. The period of time for which the analysis of prototype wave marigrams was performed was 13 October 1945 to 13 April 1946. Gaging station 9 was located in the Navy Harbor at Terminal Island on the south end of Pier 2; station 10 was located at the north end of East Channel; and station 11 at the north end of West Channel. Locations of these stations are shown on plate 1. Plate 4 shows average and maximum wave heights of each wave period recorded during the time for which analysis was made, exclusive of those waves (tsunami*) which occurred during 1-3 April 1946. Plate 5 shows average and maximum wave heights of each period wave which occurred at the three gaging stations during the period 1-3 April 1946. These waves were omitted from the wave-height data shown on plate 4 because they occur very rarely and are not considered significant in connection with the subject problem. The waves which occurred 1-3 April 1946 were recorded and analyzed and are shown separately in this report as a matter of interest to engineers engaged in harbor design.

22. In the analysis of prototype wave marigrams all waves were recorded which had heights of 0.05 ft or more (the wave periods which

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* "The Tsunami of April 1, 1946, in the Hawaiian Islands", by G. A. Macdonald, F. P. Shepard, and D. C. Cox. Pacific Science, vol 1, no. 1, Jan. 1947.

occurred 1-3 April 1946 were included because they were not exceptional with respect to period, and it was not thought worthwhile to separate them due to the short length of time they existed relative to the 6-month analysis period). Waves having heights less than 0.05 ft were omitted because they could not be readily discerned on the marigrams. Wave traces which occurred on the marigrams were rarely of a constant period for any considerable length of time. In fact, it was seldom that any two successive wave periods were exactly the same. However, waves in any given wave train were approximately of the same period, and the average of the periods in a wave train was used in this study. Although at times the number of wave cycles in a wave train was as great as 40, there were rarely more than 25 cycles, and the average number was about 10. This refers to long-period waves only. The short-period waves -- in this case waves with periods from 5-18 seconds -- were found to occur nearly 100 per cent of the time with practically constant wave periods within the wave trains. The widths of the columns in the graphs (plates 3-5), as measured on the wave-period axis, show the range of periods into which the different long-period waves were grouped when they were measured from the prototype wave marigrams.

23. Short-period waves generated by local and distant storms are not presented on the graphs referred to above. Although waves with periods from 5 to 18 seconds do occur almost constantly, they are not critical insofar as the present problem is concerned due to the sheltered location of the problem area. The locations of the gaging stations were chosen to show the occurrence of long-period waves rather than the amplitudes of short-period waves. However, station 10 is located at a position

satisfactory for determining occurrences of short-period waves, although its sheltered position precludes the obtaining of short-period primary wave heights.

Wave Periods and Percentage of Time Occurring

Short-period waves

24. It was found that short-period waves with periods ranging from about five to eighteen seconds occurred in the problem area about ninety-seven per cent of the total 6-month analysis period. About eighty per cent of these waves had periods from 13 to 18 seconds and about seventeen per cent had periods from 5 to 12 seconds. About seventy-seven per cent of all short-period waves recorded were of the 15-second type (14-16 seconds).

Long-period waves

25. Station 9. The different long-period waves and the per cent of time waves of each period were found to occur at this gaging station are shown on plate 3. Long-period waves with wave heights of 0.05 ft or greater were found to occur about ten per cent of the time. The periods of these waves fell generally into two groups: (a) periods ranging from 1 to 6-1/4 minutes, and (b) periods ranging from 20 to 35 minutes. The 3-1/2- to 4-minute period waves occurred more frequently (about seven per cent of the time) than any of the other waves recorded at this station; the 6-minute wave which occurred about two per cent of the time was the next most frequent. A 30-minute wave occurred about one-half of one per cent of the time.

26. <u>Station 10</u>. The per cent of time each long-period wave occurred at station 10 is shown on plate 3. It was found that long-period waves with heights of 0.05 or greater occurred in East Channel about twenty-five per cent of the time. The wave periods which occurred most often fell into two general groups: (a) waves with periods from about 1-3/4 to 2-1/2 minutes, and (b) waves with periods of 6 to 7 minutes. Wave periods which occurred more often in the two groups were 2-1/4- and 6-1/2-minute period waves, respectively. A few waves were found to occur with periods of about 11, 30 and 75 minutes.

27. <u>Station 11</u>. The per cent of time each long-period wave occurred at station 11 is shown on plate 3. As in the case of station 10, it was found that long-period waves, with heights of 0.05 or greater, occurred at this station about twenty-five per cent of the time. However, the grouping of wave periods with respect to frequency of occurrence was found to be somewhat different from that of station 10. Wave periods which occurred more often at station 11 were: (a) 1-1/2 to 2 minutes, (b) 3-1/2 to 4 minutes, and (c) 8 to 11 minutes. The wave periods occurring more often within these three groups were 1-3/4 minutes, 3-3/4 minutes, and 9 and 10 minutes, respectively. The 3-3/4-minute waves occurred more often at this station than any other wave in the spectrum.

<u>Normal Long-Period Wave Heights</u>

28. Wave heights of the normal long-period waves which were found to occur at gaging stations 9, 10, and 11 are shown on plate 4. Plate 4 shows the heights of waves which occurred between 13 October 1945 and 13

April 1946, exclusive of those wave heights which occurred on the dates 1-3 April 1946.

Waves at station 9

29. Importance of waves at station 9. The heights of long-period waves which obtained within the newly constructed Navy Harbor at Terminal Island were of interest in connection with the Point Fermin problem because they can be used as a basis for determining the severity of the wave heights which occurred within the Point Fermin problem area. The mole at Terminal Island was constructed so as to be impervious to long-period waves, and it completely surrounds the Navy Harbor except for a navigation opening about 800 ft in width. The Navy Department designed and constructed the mole in such manner that it was to be expected that the harbor thus formed would be very satisfactory in its wave- and surge-action characteristics; this has been found to be the case. Due to the small width and favorable location of the navigation opening into the harbor at Terminal Island, the amount of short-period wave energy which gains entrance to the harbor area is practically nil. Also, except for rare instances, the amount of long-period wave energy which finds its way into the harbor is very small, as shown by results of the prototype wave study. There has been no report of troublesome or damaging surge action to ships moored at piers in the Navy Harbor since construction of the Terminal Island mole. Thus, it was very advantageous that a gaging station was in operation within the Navy Harbor during the same period for which the prototype wave analysis was performed for the Point Fermin problem area. This fact allowed a comparison between wave conditions in

a harbor known to be functioning satisfactorily with conditions in an area proposed for wharf construction. Moreover, both areas are within the same general locality, both are within the outer breakwater system in San Pedro Bay, and both are subjected to the same external wave impulses.

30. Wave heights. Both the average and maximum wave heights of the normal long-period waves which obtained at station 9 during the 6-month analysis period are shown on plate 4. Excepting the 30-minute wave, which occurred very rarely, there was no wave period with an average wave height exceeding 0.1 ft. The arithmetical mean of the average wave heights was 0.08 ft. The absolute maxima are appreciably larger than 0.1 ft only in the case of a few wave periods. The maximum wave heights which are considered most important -- because they may be due to a condition of resonance for wave periods within the range that has been known to cause troublesome and damaging surge action -- are the 0.25-ft wave heights (absolute maxima) for the 3.75- and 4-minute period waves. The maximum height of the 6-minute waves was also 0.25 ft and should be considered, although there has never been any damage to ships in this area known to be due to waves with periods of this magnitude. Higher maximum wave heights were recorded for wave periods of 20, 25, and 30 minutes. However, waves of these periods and amplitudes occur very rarely, and the periods are so long that their effect on moored ships probably is not critical; therefore, they are not considered to be significant with respect to the problem under investigation. Rather, it is the average normal wave heights within the range of periods known to have been troublesome to ships moored at piers and wharfs which are considered

most important in the day-to-day action of surge waves on ship movements. They are the waves whose heights are compared in this study.

Waves at station 10

31. Importance of waves at station 10. The East Channel of the outer Los Angeles Harbor is known to possess very undesirable surge characteristics. The rectangular shape of the channel, its length, and the position and shape of its navigation entrance, all seem to be factors in sustaining, and probably magnifying, the surge waves occurring in the San Pedro Bay area. East Channel is situated adjacent to, and has the same alignment as West Channel which is part of the immediate problem area. Surge waves which occur in East Channel, therefore, may be used as another convenient datum to which surge action in the Point Fermin problem area may be properly compared. Thus, on the one hand we have a record of the surge characteristics of a harbor area known to be functioning satisfactorily in the protection of ships moored at piers from the effects of surge action (Navy Harbor at Terminal Island -- station 9), and, on the other hand, similar and concurrent data are available which show the surge characteristics of a harbor area known to be unsatisfactory (East Channel -- station 10). Wave data obtained at gaging stations 9 and 10, therefore, are used to predict the surging action of ships moored at the proposed supply depot wharf. Another reason for locating a gaging station in East Channel was to insure that sufficient data would be available to determine whether the proposed supply depot would affect surge action in that channel.

32. Wave heights. The average and maximum wave heights obtained

at station 10 are shown on plate 4. During the 6-month analysis period the arithmetical mean of the average wave heights for all long-period waves recorded at this station was 0.2 ft. Maximum wave heights were considerably higher, in one instance being as high as 0.9 ft. The results of wave-record analysis for this station show why the East Channel has a rather bad reputation for surge action. It was found during the Terminal Island investigation that there was a good correlation between troublesome and damaging ship movements and the height of long-period waves. It was found that waves whose periods averaged about two and one-half minutes with wave heights of 0.2 ft or more were accompanied by surges whose horizontal amplitudes were usually sufficient to cause troublesome or damaging ship movements. In the East Channel, waves with periods from about one to ten minutes occur about twenty-five per cent of the time with average wave heights of 0.2 ft.

Waves at station 11

33. Importance of waves at station 11. Station 11 was positioned at the north end of West Channel because of the location of this channel relative to the Point Fermin problem area. Surge waves which will obtain along the proposed wharf should be a function of the waves which now exist in the West Channel before construction of the proposed supply depot fill. The results of prototype wave analysis for station 11, together with the Point Fermin model test results of base-test conditions and conditions with the proposed plans in place, are used in this investigation to predict the magnitude of surge waves which will obtain if the supply depot is constructed according to one of the plans tested.

Using these data to predict the magnitude of surge waves which will obtain after installation of a proposed plan, and using the magnitude of the waves found to occur at stations 9 and 10 together with the ship-surge characteristics of the two harbor areas represented by these stations, is the method selected for predetermining the ship-surge characteristics of the proposed supply depot wharf. This method of reasoning could also be applied to determining proper corrective measures, in the form of realignment of the proposed wharf line or the addition of protective breakwaters, if the results of this investigation are considered to indicate that undesirable surge conditions will obtain from the installation of the supply depot as planned.

34. Wave heights. Average and maximum wave heights obtained at station 11 are shown on plate 4. In only one instance did an average wave height at this station reach the critical magnitude of 0.2 ft, and this was for the relatively long wave period of 25 minutes which occurs very rarely. The arithmetical mean of average wave heights was 0.12 ft; this compares with 0.08 ft for station 9, and 0.2 ft for station 10. The largest maximum wave height of the different long-period waves which occurred at station 11 during the 6-month analysis period was 0.8 ft for 10-minute waves. Maximum wave heights at station 11 were about of the same magnitude as those at station 10, but average wave heights at station 11 were lower, being intermediate between the average of 0.08 ft for station 9 and 0.2 ft for station 10.

Waves Occurring 1-3 April 1946

35. Waves with abnormal wave heights, which accompanied an ocean-

bottom disturbance near the Aleutian Islands, existed in the problem area 1-3 April 1946. A sea-bottom movement, which propagated very large waves with periods varying from about 2-3/4 to 13 minutes (a few 30-minute period waves were either generated, or excited to abnormal amplitudes, by the disturbance), occurred* near a point 45 nautical miles south of the tip of the Alaskan mainland at about 0430 (PST), 1 April 1946. Waves of abnormal heights appeared on the marigrams for station 10 at about 1100 (PST), 1 April 1946. It is estimated that the distance which the waves traveled from the epicenter to San Pedro Bay was 2070 nautical miles. The first waves reached the problem area in about six and one-half hours after the calculated time of the disturbance. Thus, the faster of the waves propagated traveled at a rate of nearly 320 knots. The largest of the waves recorded at the three gaging stations occurred at stations 10 and 11. The largest waves at station 10 occurred between 1600 and 1700 (PST), 1 April. These waves had a period of about eight and one-half minutes and a maximum height of nearly four feet. The largest waves at station 11 occurred between 1200 and 1300 (PST), 1 April, with a period of about ten minutes and a maximum height of 4-1/4 ft. The waves recorded at station 9 were much smaller, the largest having periods of about six and thirty minutes with wave heights of about one foot.

36. The heights and periods of the abnormal waves which occurred at the three gaging stations are shown on plate 5. Arithmetical means of the average wave heights were 0.45 ft, 1.25 ft, and 1.10 ft, for stations

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* The epicenter of the accompanying earthquake has been located by the Coast and Geodetic Survey at latitude 53.5° N and longitude 163° W, and the time as 12:29 Greenwich time (see Pacific Science, Jan. 1947).

9, 10, and 11, respectively. The maximum waves which occurred at these stations had heights of 1.30 ft, 3.80 ft, and 4.25 ft, respectively. A comparison of the normal and abnormal wave heights for the three gaging stations is shown below:

	Normal Ht in Ft		Abnormal Ht in Ft	
Station	Average	Maximum	Average	Maximum
9	0.08	0.45	0.45	1.30
10	0.20	0.90	1.25	3.80
11	0.12	0.80	1.10	4.25

When it is remembered that the critical wave height of long-period surge waves for ships moored at piers and wharfs is about 0.2 ft, the magnitude of the abnormal waves which occurred 1-3 April 1946 is very impressive although no damage to ships or harbor installations, due to these waves, was reported.

Discussion of Results

37. The prototype wave analysis was made to determine the frequency of occurrence and respective wave height for different long-period waves which occur in the Point Fermin problem area. These data were used, together with similar prototype data obtained in other existing harbor areas within the outer breakwater system at San Pedro Bay (stations 9 and 10), and model data obtained in the Point Fermin investigation, to determine surge characteristics likely to obtain at the proposed supply depot wharf. The conclusions reached from results of the prototype and model investigations were predicated upon the following premises: (a) the Terminal Island harbor is functioning satisfactorily with respect to surge action; (b) the East Channel has very undesirable surge characteristics; and

(c) a 0.2-ft surge wave with a period from 2 to 3 minutes is critical with respect to ship movements at piers and wharfs.

38. It can be shown mathematically that the horizontal velocity of the water particles resulting from long-period wave surge action is not a function of wave period, but is directly proportional to wave height when depth of water remains constant. The size of ship, method of mooring, type of fender system, and type and position of camels, also determine the extent of damage which will result for a given size surge wave. Also, it is fairly certain that the relation between length of mooring lines and wave period has considerable bearing on the amount of damage which will obtain for a given ship, wave height, and type of fender system and camels. The length of mooring line is usually a function of tide range which is practically constant within the areas studied in this investigation. For the present problem, the size of ship, method of mooring, type of piers, wharfs, fender system and camels, and depths of water can be considered constant for the harbor areas represented by stations 9, 10, and 11. Therefore, it is logical to assume that the critical wave height of 0.2 ft, which was determined for ships at Terminal Island, can be used as a criterion by which the efficacy of the proposed supply depot plans can be judged.

39. Results of the prototype wave analysis show that the magnitude of long-period waves in the West Channel (which is a measure of the surge characteristics of waters adjacent to the proposed supply depot wharf) is intermediate between the size of the waves which occur in the Terminal Island harbor and the East Channel. Therefore, if surge characteristics of the water adjacent to the proposed supply depot wharf are to be

satisfactory, the proposed fill should reduce, or at least not increase, the amount of surge action in the West Channel. If the installation of the supply depot should increase to any appreciable extent the surge action in the West Channel, unsatisfactory surge characteristics for the supply depot wharf can be predicted.

40. It is interesting to note that, of the long-period waves which were found to occur more frequently at the three gaging stations, only one wave period was common to more than one station. This was the 3-3/4-minute wave which was found to occur a high percentage of the time at both stations 9 and 11. The fact that wave spectrums for different locations in a given harbor area are not necessarily similar is interesting and, doubtless, very significant. An understanding of the reasons for this apparent paradox would throw considerable light on the problems concerning the action and methods of treatment of long-period waves in harbors. A logical explanation can be reached if it is assumed that long-period waves with periods covering the combined spectrums of all portions of a harbor area are propagated into the harbor from external sources. It is not necessary for the purpose of explaining the immediate question to know the source of these long-period waves. However, knowledge of their source would be desirable in that the problems of harbor design relating to wave and surge action could be placed on a more scientific basis. Assuming that waves of many different periods are propagated into the harbor area through navigation openings and voids in the rubble breakwater, the reason that one wave period is found to occur more often in one portion of the harbor than another (stated differently, the reason that wave spectrums of all areas in a harbor are not

similar and are not the same as the spectrum of the waves entering the harbor) can be explained by using an electrical analogy. The effects of the different bodies of water within the harbor can be compared with the action of rather poor filters which reduce the amplitude of some of the waves entering, filter out some altogether, and allow others to enter uninhibited; also, for particular wave periods, some of the bodies of water act as resonators. Viewing the problem in this light, it can be expected that waves with periods approaching the effective fundamental oscillating period (or one of its harmonics) of a body of water in one part of a harbor will be found to exist more often, at least in measurable quantities, in this part of the harbor than in another body of water within the harbor having different resonant periods. This does not mean that a body of water within a harbor will not oscillate or sustain wave periods other than its fundamental oscillating period or one of its harmonics (forced oscillation). Rather, it appears that for a given wave impulse of a certain period from without, the bodies of water whose fundamental, binodal, or trinodal, etc. periods were more nearly equal to the period of the activating impulses would tend to oscillate more freely with larger amplitudes and with smaller damping coefficients. The bodies of water within a harbor with natural fundamental periods more nearly resonant with an impulse from without would tend to have larger amplitudes, and the oscillation would tend to sustain itself longer, than for bodies of water which were not resonant to the same impulse. A forced oscillation would have smaller amplitudes and a larger damping coefficient.

PART IV: RESULTS OF MODEL TESTS

41. The results of model tests are shown on plates 6-32. Plates 6-13 show results of the short-period (15 second) wave-height tests; plates 14-21 show results of the 2.5-minute period wave-height tests; and plates 22-32 show results of the frequency-response tests.

Short-Period Wave Tests

Base tests

42. Short-period wave tests were performed with existing prototype conditions installed in the model using 15-second waves 12 ft in height from the directions of south 22-1/2 deg west, south, and southeast.

Fig. 5. 15-second waves from the southeast direction

Figure 5 shows 15-second waves entering the west navigation opening in the outer breakwater from the southeast direction. As shown on plates 6-8, the largest waves which obtained in the problem area (vicinity of the proposed supply depot wharf) were about 1, 2, and 3 ft, respectively, for the directions of south 22-1/2 deg west, south, and southeast. In the prototype the larger per cent of the short-period waves approach the outer breakwater system in San Pedro Bay from the south-southwest quadrant. Relatively high storm waves rarely approach the harbor from the southeast direction.

43. It can be seen from results of these tests that very little short-period wave energy reaches the problem area from any of the directions of approach. Therefore, unless the rubble-protected fill of the selected plan causes considerable wave reflection which results in the clapotis-type wave (whose wave heights are about double the unreflected wave heights), no trouble due to short-period wave action should occur.

Plan 1

44. Results of the 15-second wave-height tests of plan 1 are shown on plates 9-11. By comparing plan-1 wave-height contours with those of the corresponding base test it can be seen that the comprehensive plan would not increase wave heights along the proposed wharf. The maximum waves which could be expected would be about 3 ft in height, and it requires a southeast primary wave 12 ft in height or greater to result in a wave of this height at the proposed wharf. The frequency of occurrence of waves 12 ft high from the southeast direction is about twice yearly. Therefore, the action of ships at the proposed plan-1 wharf would be

quite satisfactory insofar as short-period waves are concerned (waves reaching problem area from other directions are smaller than those due to southeast storms).

Plan 2

45. Results of the 15-second wave-height tests for plan 2 are shown on plates 12 and 13. The largest waves which would obtain along the plan-2 wharf would occur at the mouth of the West Channel due to waves from the southeast. These waves would be about 2 ft in height and would occur about twice yearly. This plan would, therefore, be satisfactory with respect to ship movements due to short-period waves.

2.5-Minute Wave Tests

46. Results of the 2.5-minute wave-height tests are shown by wave-height contours on plates 14-21. Wave-height tests using 2.5-minute waves were performed for base-test conditions and with plans 1 and 2 installed in the model. These tests were made using, separately, both the south-22-1/2-deg-west and the southeast directions for waves. Tests were also made using waves from the south direction, but only for base-test conditions and plan 1. It was found that the mode of oscillation established by waves from the south direction resulted in waves of less severity in the problem area than those resulting from modes of oscillation established by waves from either the directions of south 22-1/2 deg west or southeast. The modes of oscillation which occur in the prototype are not known. Therefore, in the model, more than one mode was established by using waves from different directions, and the results of the

worst mode of oscillation were used for analysis. It was found that the mode of oscillation caused by generating waves from the southeast direction was more severe, resulting in larger wave heights in the problem area for plans 1 and 2, than for either of the other wave directions tested.

47. The primary waves used in these tests were about 3 ft in height outside the west navigation opening. Although long-period wave heights which occur in the prototype outside the breakwater are not known, it is thought that they are generally somewhat smaller than the 3-ft height which was used in the model. This does not affect the accuracy of model results, however, since the mode of oscillation is not affected by wave height to any great extent. The larger wave heights were used in the model in order to insure that measurable waves would obtain in the problem area for all tests.

48. The 2.5-minute waves were selected for testing because they had been found to be the cause of most of the troublesome and damaging ship movements which occurred at Terminal Island before the Terminal Island mole was constructed. The 2.5-minute wave tests in this model study were made using the same plunger stroke and submergence and positions of the wave machine as those used in the Terminal Island tests. Results of the prototype wave analysis showed that the West Channel is not very responsive to 2- to 3-minute period waves in its present condition. However, the analysis did show that 2- to 2-1/2-minute waves occur in the area quite frequently because they appeared on the East Channel marigrams. Therefore, if the supply depot plan selected for construction resulted in a condition whereby the West Channel became

more responsive, or resonant, to 2- to 3-minute waves, unsatisfactory mooring conditions at the proposed supply depot wharf would be indicated. Conversely, if the plan selected for construction did not increase the response of the problem area to 2- to 3-minute waves, satisfactory mooring conditions at the proposed wharf would be assured, insofar as the surging of ships due to waves of this range of period is concerned.

Plan 1

49. Selecting the worst mode of oscillation for comparison (waves from the southeast direction, see plate 19) it can be seen that installation of plan 1 increases the wave heights in the West Channel and Watchorn Basin. Therefore, the construction of plan 1 should be expected to result in undesirable surge characteristics for ships moored at the plan-1 wharf, especially if ships were moored in a nodal area for the 2- to 3-minute waves. Based on frequency of occurrence of these waves in the East Channel, troublesome or damaging surge due to 2- to 3-minute waves would occur at the plan-1 wharf about two per cent of the time.

Plan 2

50. Installation of plan 2 (alternate initial development) also increased the 2- to 3-minute wave heights in the West Channel, compared with base-test results. Therefore, as for plan 1, plan 2 could be expected to result in undesirable 2- to 3-minute surge characteristics for ships moored in a nodal area along the proposed wharf. For both plans 1 and 2 the strongest nodal area for waves of this period would be at the entrance to the West Channel.

Frequency-Response Tests

51. Results of the frequency-response tests are shown graphically on plates 22-24. These tests were performed to determine the degree of response of the bodies of water in the problem area to different period waves, ranging from about 12 seconds to 14 minutes. Comparison of the generated wave height outside the outer breakwater to wave heights which obtained in the problem area was used as a measure of the degree of response which the bodies of water have to the different period waves. Resonance characteristics are easily discernible from the results of these tests. When full resonance is obtained, the ratio tends to become exceptionally large, but is sometimes suppressed by a large damping coefficient due to friction or the breaking up of the primary wave into more than one mode of oscillation. Knowledge of damping characteristics is very limited; therefore, the method of evaluating the relative magnitude of the frequency-response ratios is based on the maximum ratio obtained. Thus, maximum resonance in the case of the present tests is indicated by the value of the ratio obtained in the East Channel for a wave period of 7-1/8 minutes (value of 7.5).

52. Frequency-response curves were prepared for West Channel, Watchorn Basin and East Channel. The response of West Channel and Watchorn Basin is of special interest in this investigation because if either of these bodies of water show resonance characteristics for wave periods known to exist in San Pedro Bay, undesirable surge action is indicated at the entrance to West Channel for either plan 1 or plan 2. Response data were obtained for East Channel as a precautionary measure

in order to prove or disprove the thesis which might be advanced that construction of the supply depot would increase the surge action which now exists in East Channel.

Base-test conditions

53. Results of the frequency-response tests for existing prototype conditions are shown on plates 22-24, together with results of plans 1 and 2. Plates 25-32 show modes of oscillation of a few of the wave periods used in the frequency-response tests. West Channel as it now exists in the prototype does not respond very readily to any wave period below 6 minutes, although a slight response is indicated for 3-3/4- and 5-3/4-minute waves; it responds very energetically to all wave periods from 6-1/2 minutes to 7-1/8 minutes, and is fully resonant to a wave period between 7 and 7-1/8 minutes. The problem area as a whole seems to be a loop area for all the longer-period waves used in the frequency-response tests (9-14 minutes). The West Channel shows resonance for wave periods of about 10-1/4, 12-1/8, and 13-1/8 minutes, and a small damping coefficient for all wave periods from 9 to 14 minutes. These seemingly resonant characteristics and small damping coefficients for the longer wave periods are not necessarily indications that West Channel itself is responsive to these waves, but they could indicate that the problem area is the loop area of a mode of oscillation for the larger body of water between the outer breakwater and the Terminal Island-Long Beach shore line. Watchorn Basin and West Channel, being a portion of this loop area, show the same frequency-response characteristics for all wave periods greater than about 6-1/2 minutes. Generally, however, the frequency-response ratio

for Watchorn Basin is slightly smaller than that of West Channel for these longer wave periods. East Channel, being somewhat nearer the first nodal area for these waves, shows less response to wave periods above about 10 minutes than either West Channel or Watchorn Basin. However, East Channel, like West Channel and Watchorn Basin, is resonant to 7-1/8-minute waves and has a smaller damping coefficient than do West Channel and Watchorn Basin, which are nearer the problem area. Watchorn Basin is resonant to 2-3/4- to 3-minute waves and shows a good response to 3-3/4-minute waves. Except for these two wave periods, East Channel is generally more responsive to wave periods up to about 9 minutes than either West Channel or Watchorn Basin.

Plan 1

54. Installation of plan 1 in the model caused West Channel to become resonant to 3-3/4-minute and 10- to 12-1/2-minute waves. Watchorn Basin became more resonant to 2-3/4-minute and 3-3/4-minute waves, and became extremely resonant, as did West Channel, to 11- to 12-minute waves. Installation of plan 1 destroyed the resonant characteristic of both West Channel and Watchorn Basin for the 7-1/8-minute waves. East Channel remained resonant to 7-1/8-minute waves with this plan installed. Plan 1 did not affect appreciably the frequency-response characteristics of East Channel, except for the 10-1/2- to 12-1/2-minute waves for which East Channel became resonant while it was not for base-test conditions.

Plan 2

55. With plan 2 installed in the model, the resonance of West Channel and Watchorn Basin to 3-3/4-minute waves was eliminated.

Watchorn Basin was still resonant to 2-3/4-minute waves, as it was for plan 1 and base-test conditions. Plan 2, like plan 1, eliminated the resonance of West Channel and Watchorn Basin to 7-1/8-minute waves, but it increased their response to 5-3/4-minute waves and caused them to become slightly resonant to 6-1/2-minute waves. West Channel and Watchorn Basin are responsive to most all wave periods above about 8 minutes and are resonant to 10- to 10-1/2- and 11-1/2- to 12-1/2-minute waves, with plan 2 installed. Compared with plan 1, plan 2 did not change appreciably the frequency-response characteristics of East Channel.

Discussion of Results

56. Results of the 15-second wave tests, and the high damping coefficient indicated for short-period waves by results of the frequency-response tests, show that the proposed wharf for both plans 1 and 2 has excellent protection from waves of this type which are propagated from the south to southwest directions. Local storm waves from the southeast direction result in waves at the proposed wharf with maximum heights of about 3 ft. These waves occur very rarely, however, and are not thought to be of sufficient magnitude nor frequency of occurrence to require modification or relocation of the proposed supply depot. Neither is additional short-period wave protection in the form of breakwaters or wave traps considered necessary.

57. The 2.5-minute wave-height tests and the frequency-response tests for the 2- to 3-minute waves show that plan 1 does not increase existing surge conditions in West Channel for a mode of oscillation established by waves from the south direction. Plan 1 did increase

2.5-minute wave heights in Watchorn Basin, and the frequency-response tests showed that Watchorn Basin was resonant to 2-3/4-minute waves, with either plan 1 or plan 2 installed in the model. Results of the 2.5-minute wave-height tests showed that both plans 1 and 2 increased surge conditions in West Channel and Watchorn Basin for modes of oscillation extablished by waves from the southeast and southwest directions. Results of prototype wave analysis showed that 2- to 3-minute waves do not occur in West Channel very often, but that they do occur frequently in East Channel. This indicates that waves of this period are present in the problem area but that West Channel, as it now exists, does not respond readily to waves of this period. As a result, 2- to 3-minute waves in West Channel are seldom of sufficient amplitude to be measured on prototype wave marigrams. Since plans 1 and 2 cause wave heights of 2-1/2-minute waves to increase in West Channel and Watchorn Basin, and since the prototype wave analysis shows that waves of this period do occur in the vicinity of the problem area, it is believed that considerable surge action due to these waves could be expected to occur at the proposed wharf with either plan 1 or plan 2 installed.

58. The frequency-response tests showed that both West Channel and Watchorn Basin are resonant to 3-3/4-minute waves with plan 1 installed in the model. Installation of plan 2 eliminated this condition. Prototype wave analysis showed that waves of 3-3/4-minute period occur in the problem area a relatively high percentage of the time; therefore, considerable surge action due to these waves is indicated for plan 1. Plan 1 caused both West Channel and Watchorn Basin to become resonant to 11- to 12-minute waves, and plan 2 caused these bodies of water to become

resonant to 10- to 10-1/2- and 11-1/2- to 12-1/2-minute waves. The prototype wave analysis shows that waves of these periods do occur in the problem area, although they do not occur as often as 3-3/4-minute waves. Therefore, some surge action probably will occur a few times during the year due to these longer period waves. However, it is not known whether surge due to periods of this magnitude is capable of resulting in as much damage to ships and piers as occurs for the 2- to 3-minute waves. For equal wave heights the velocity of the surge currents would be the same, but the horizontal amplitude of the longer-period waves would be much larger. It may be that the mooring lines which are commonly used in harbors in this vicinity are of such lengths, in relation to the horizontal amplitudes of these longer-period waves, to preclude damage to ships or fender systems for waves of this type. Very little is known about this aspect of the problem, except that there have been no instances observed in San Pedro Bay harbors where damage to ships has been caused by surges due to waves with periods greater than about four minutes. There is much need for research designed to throw more light on this question.

59. The proposed supply depot should not affect to any great extent surge characteristics of East Channel. Installation of the supply depot would reduce the storage of the whole problem area for longer-period waves, and, because this area is a loop area for wave periods above about nine minutes, the reduction of storage caused by filling the supply depot area would cause the wave heights, and therefore surge currents, to be increased in the East Channel to some extent for these longer-period waves.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

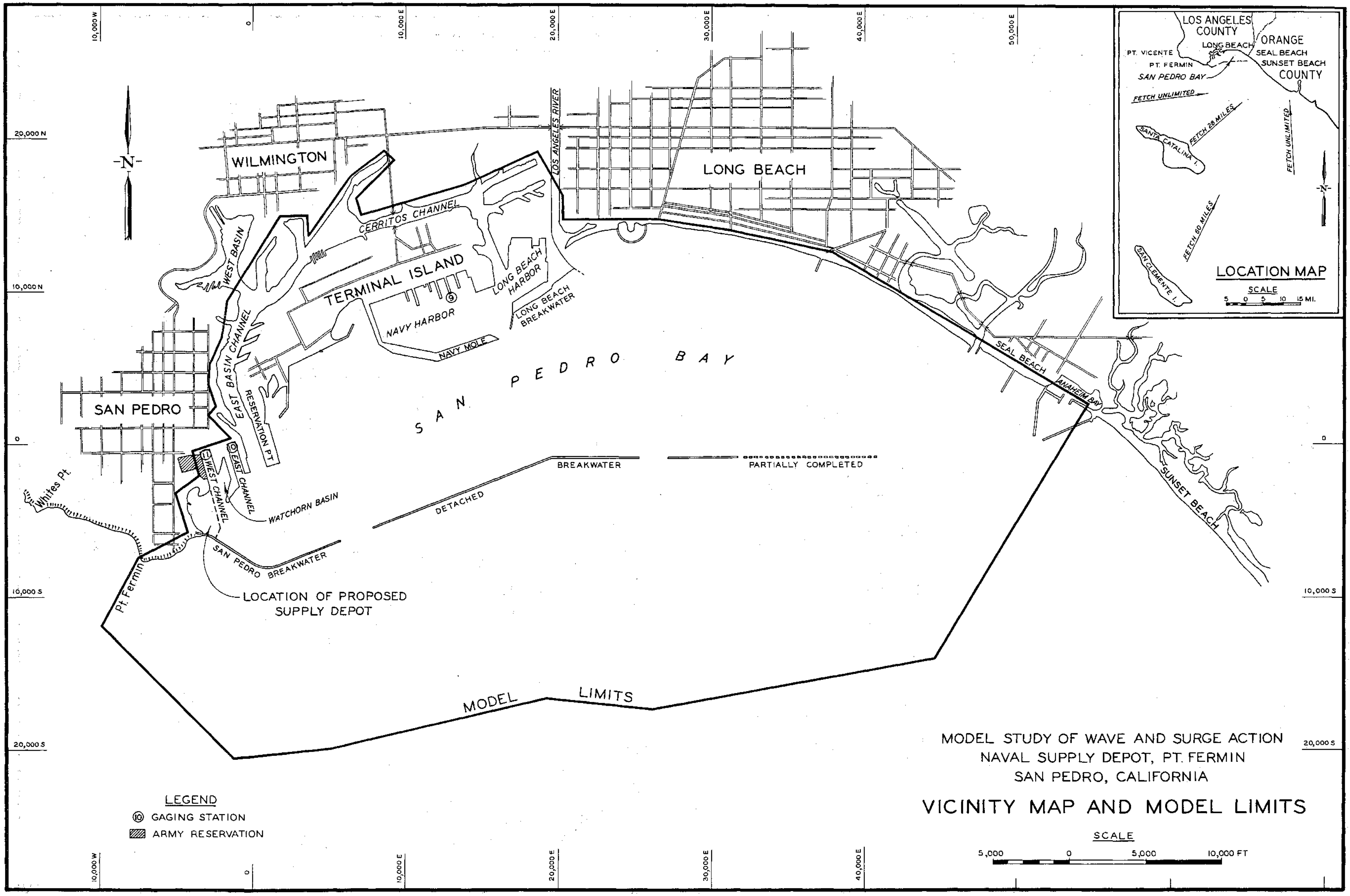
60. It is concluded from results of the model study and the prototype wave investigation that:

- a. The outer breakwater system in San Pedro Bay will provide sufficient protection to the proposed supply depot from short-period waves.
- b. Plan 2 is slightly better than plan 1 with respect to long-period surge action.
- c. Neither plan 1 nor plan 2 will be as satisfactory with respect to surge action as the existing Terminal Island Harbor.
- d. Surge conditions along the proposed supply depot wharf (either plan) will be nearly as undesirable as the conditions which now exist in East Channel (except for wave periods of 6-1/2 to 7-1/2 minutes).
- e. Construction of the supply depot (either plan) will not materially affect ship-surge conditions in East Channel.
- f. If relatively bad surge conditions cannot be tolerated at the supply depot wharf, additional model tests should be performed to determine whether some breakwater plan can be designed which would reduce surge action to an acceptable degree, or whether the supply depot should be relocated.

Recommendations

61. If it is desired that loading and unloading conditions at the proposed supply depot wharf be comparable to those existing in the Terminal Island Harbor, it is recommended that construction of the depot be postponed until further model tests can be performed to determine whether a plan can be designed which would materially reduce the predicted surge action along the proposed supply depot wharf.

PLATES

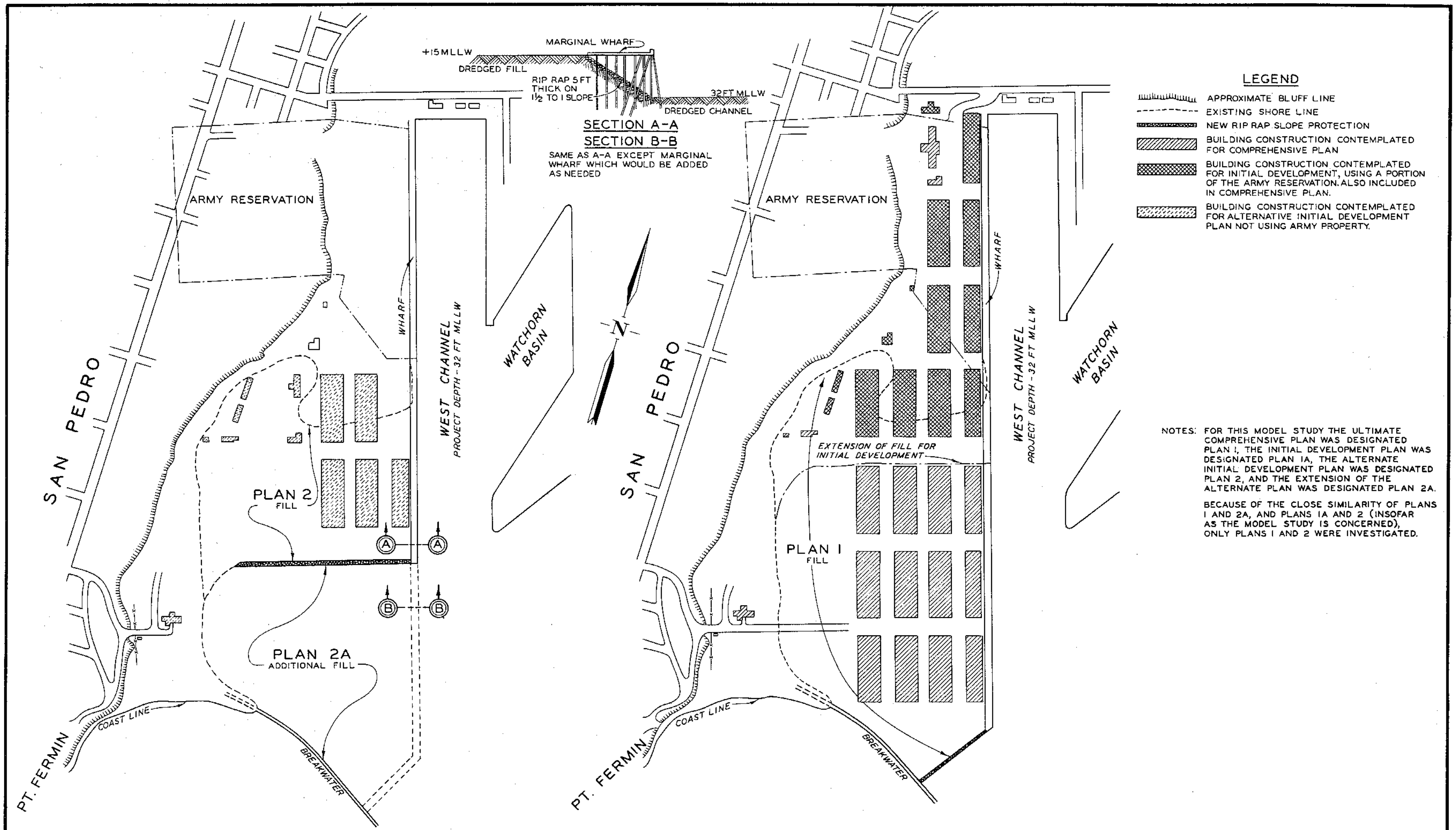


MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

VICINITY MAP AND MODEL LIMITS

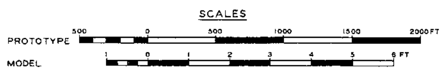
PLATE 1

PLATE 2



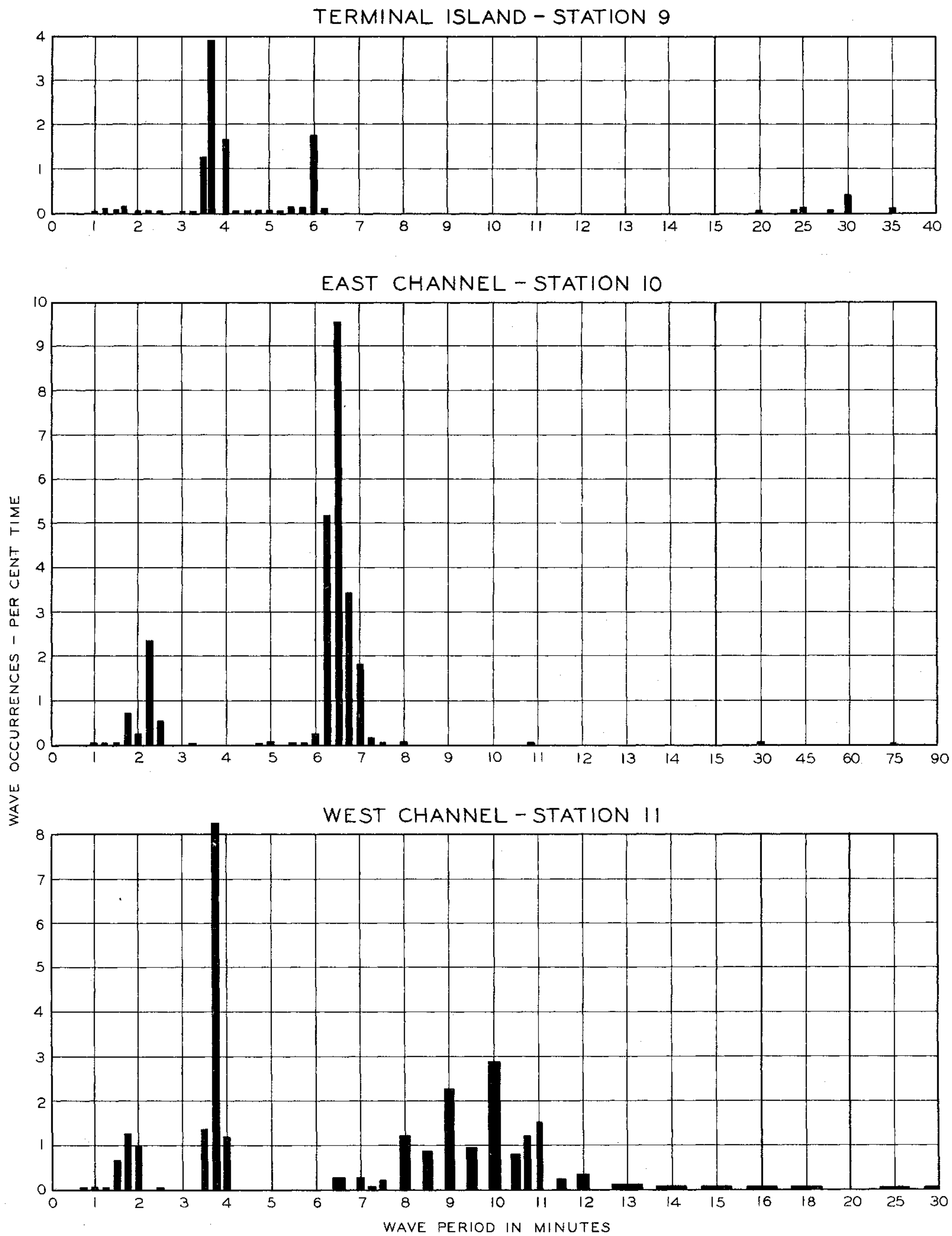
PLANS 2 AND 2A
ALTERNATE INITIAL DEVELOPMENTS

PLANS I AND IA
COMPREHENSIVE AND INITIAL DEVELOPMENTS



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

PLANS OF DEVELOPMENT



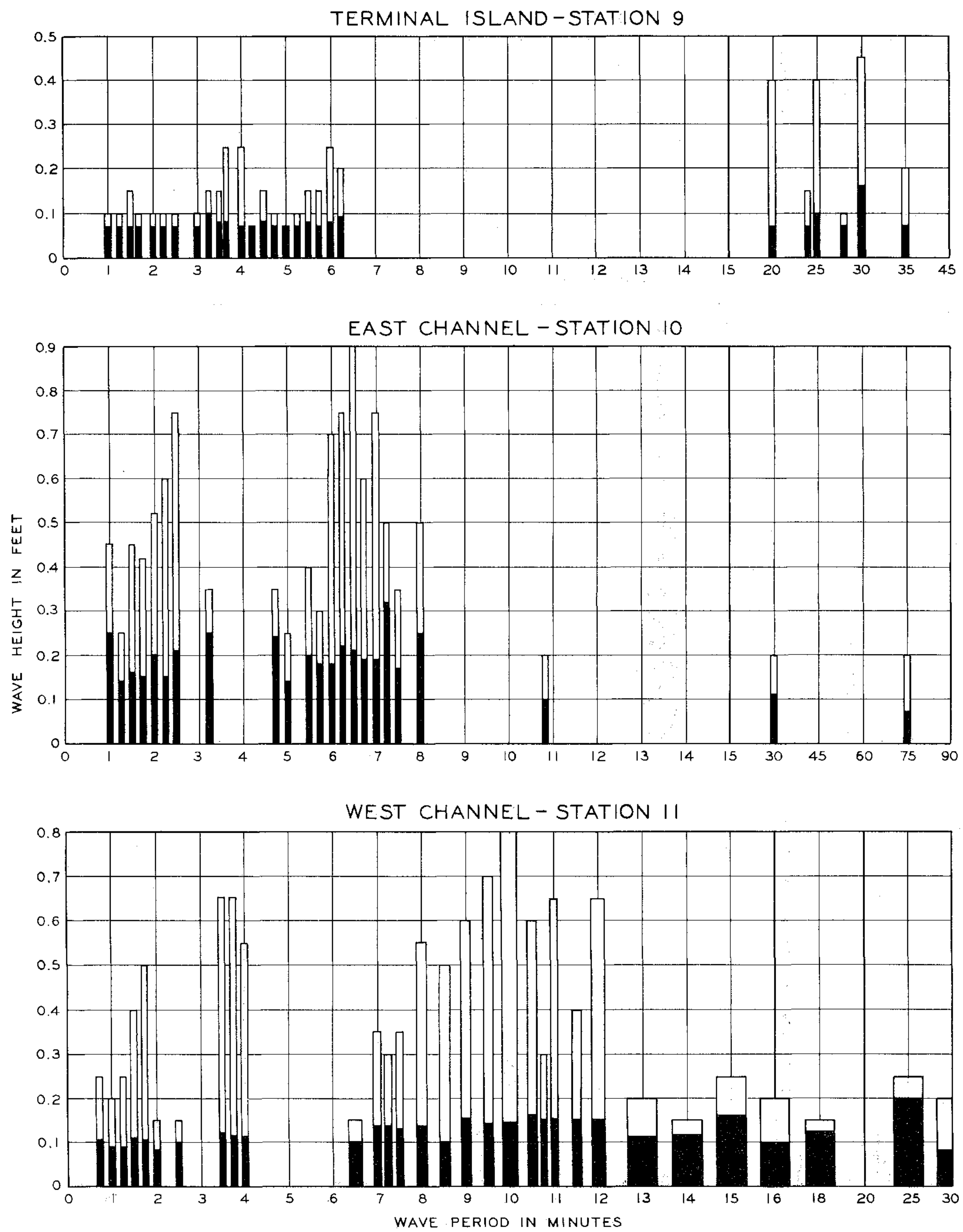
NOTE: WAVES SHOWN INCLUDE THOSE OCCURRING 1-3 APRIL 1946.

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

PROTOTYPE WAVE ANALYSIS

OCCURRENCE OF DIFFERENT PERIOD WAVES

13 OCTOBER 1945 - 13 APRIL 1946



LEGEND

AVERAGE WAVE HEIGHT

MAXIMUM WAVE HEIGHT

NOTE: WAVES SHOWN ARE EXCLUSIVE OF THOSE OCCURRING 1-3 APRIL 1946.

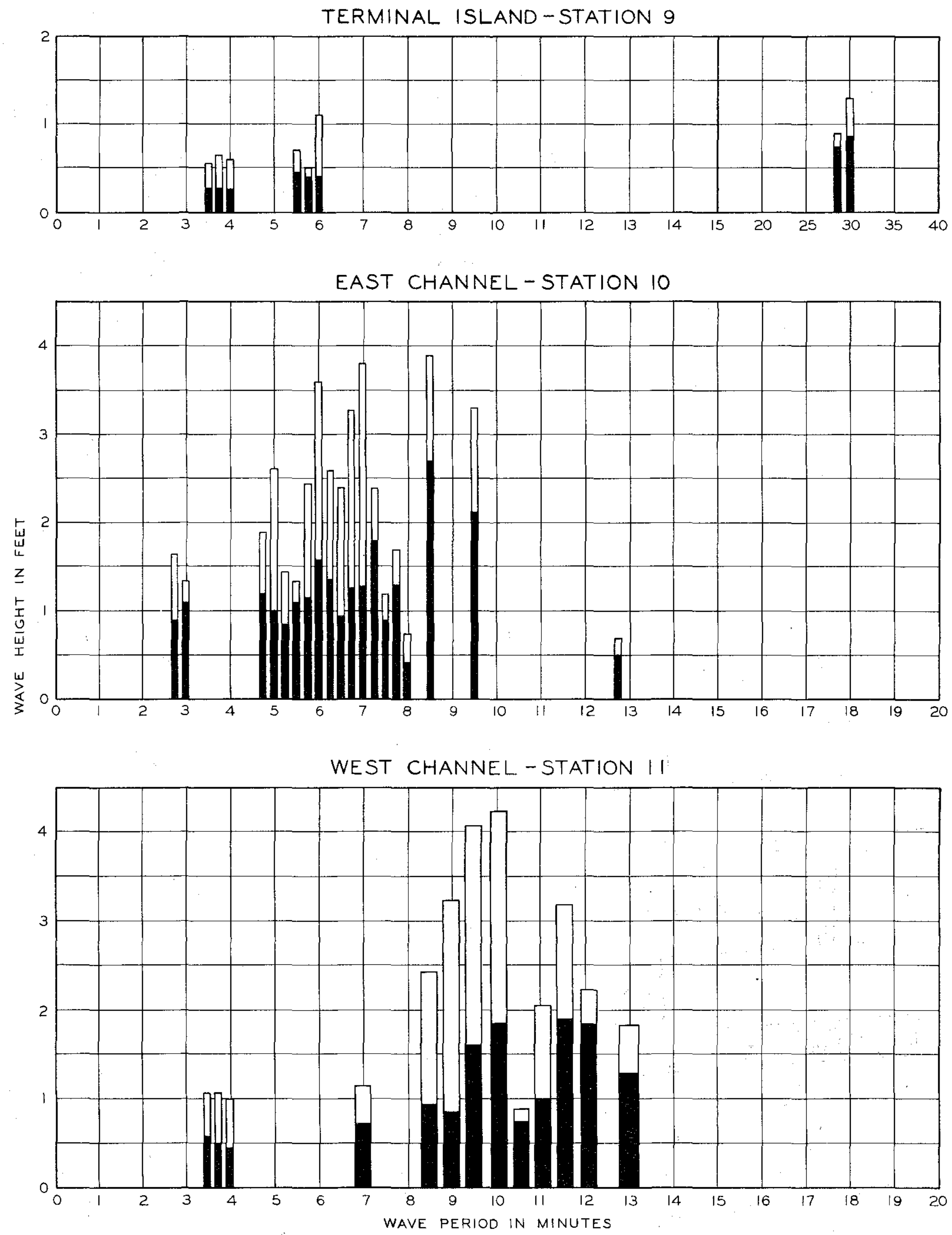
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

PROTOTYPE WAVE ANALYSIS

WAVE HEIGHTS AND PERIODS

13 OCTOBER 1945 - 13 APRIL 1946

PLATE 4



LEGEND

AVERAGE WAVE HEIGHT

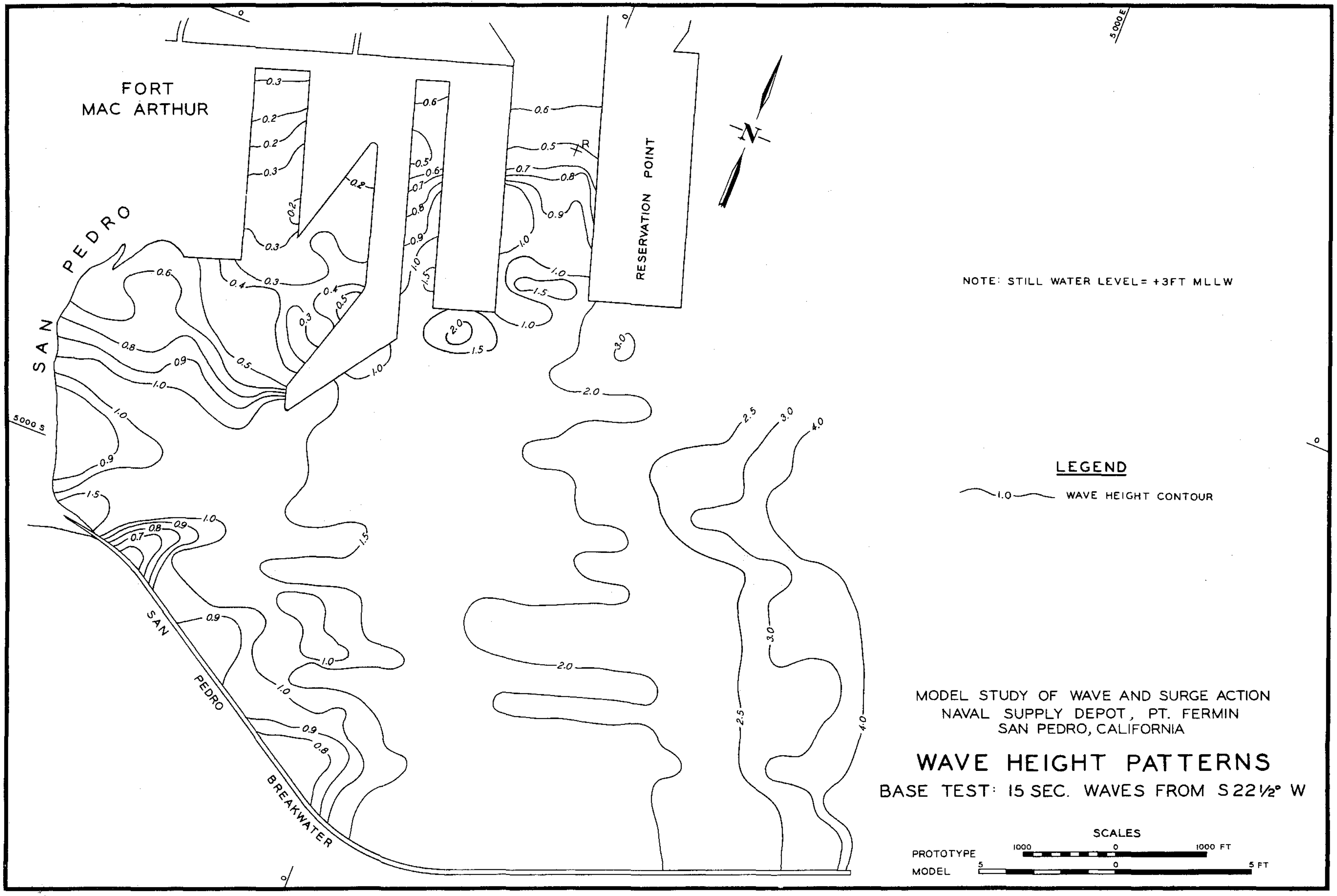
MAXIMUM WAVE HEIGHT

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

PROTOTYPE WAVE ANALYSIS

WAVE HEIGHTS AND PERIODS

1 - 3 APRIL 1946


FORT
MAC ARTHUR
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
BASE TEST: 15 SEC. WAVES FROM S 22½° W
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT
5000 S
5000 E
N

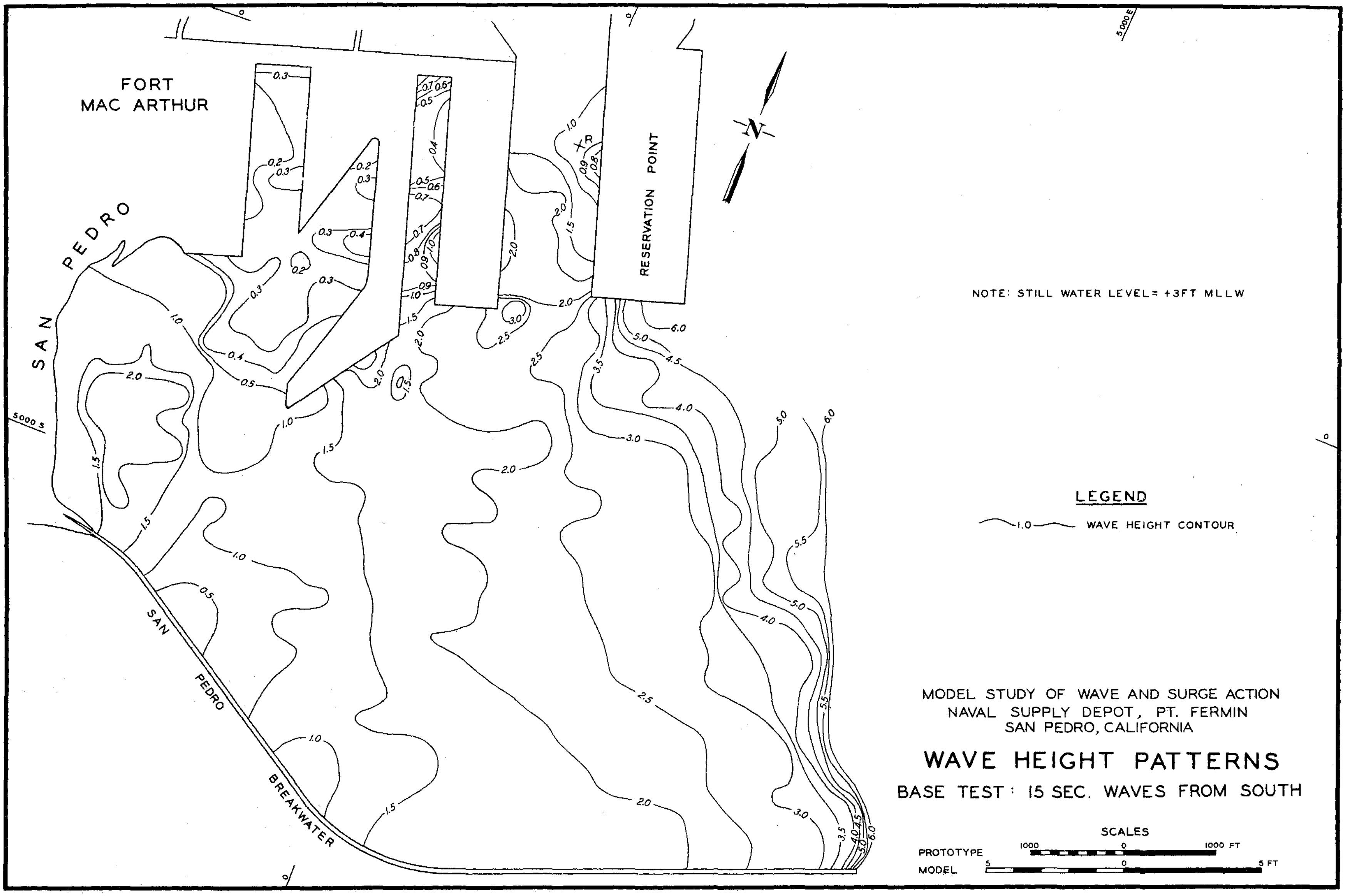
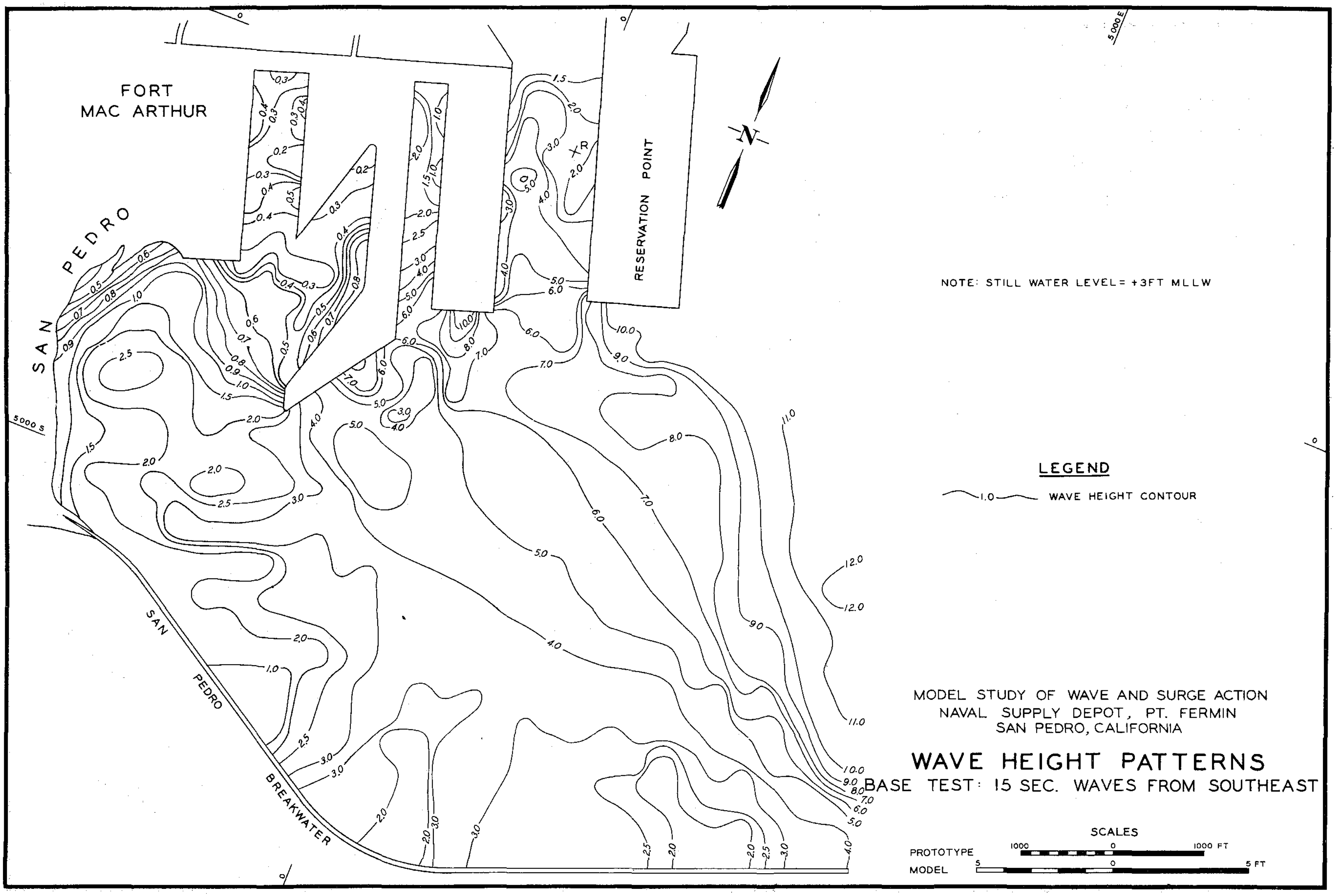

FORT MAC ARTHUR
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
BASE TEST: 15 SEC. WAVES FROM SOUTH
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

PLATE 7

PLATE 8



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHT PATTERNS
BASE TEST: 15 SEC. WAVES FROM SOUTHEAST

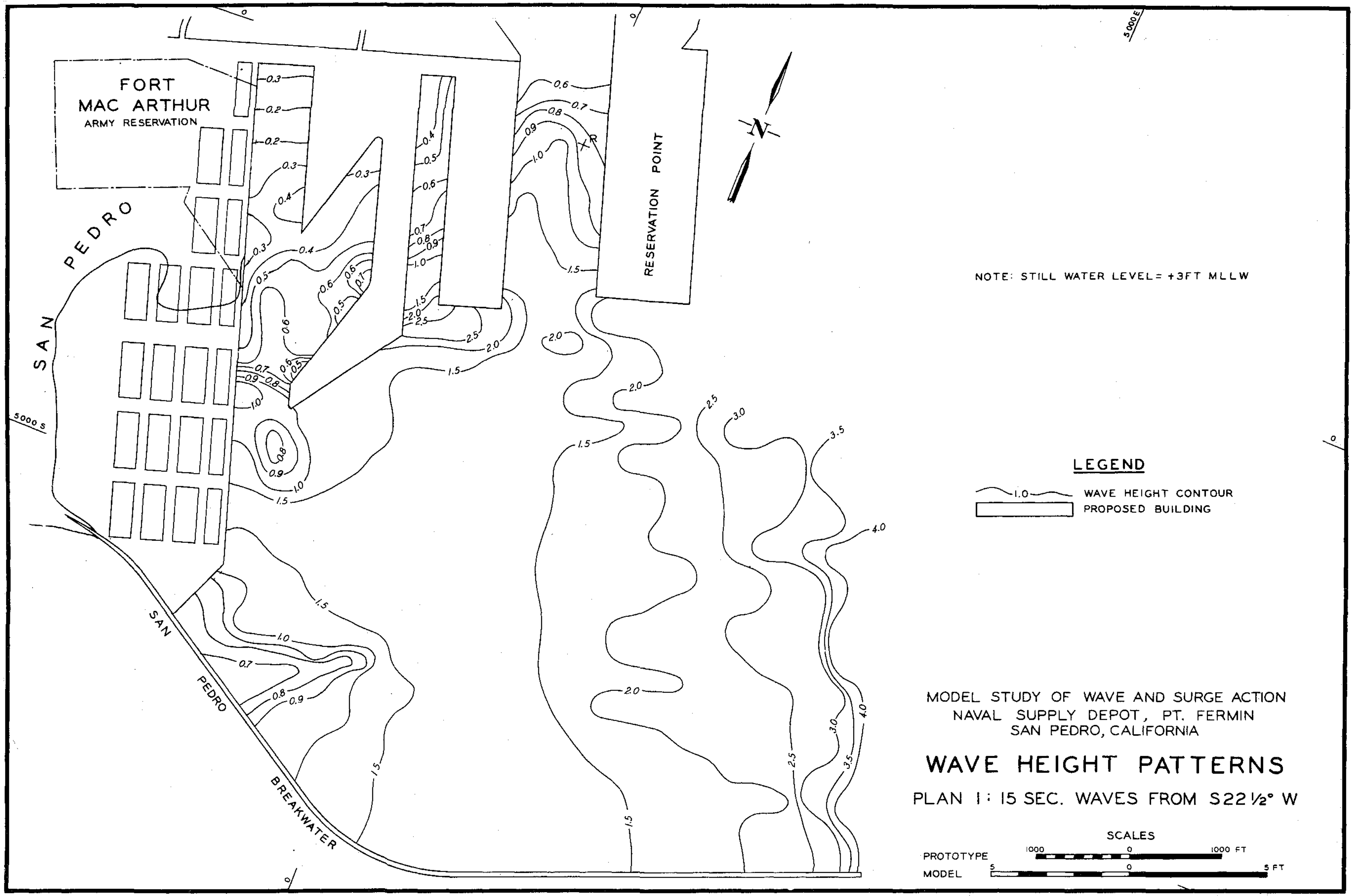
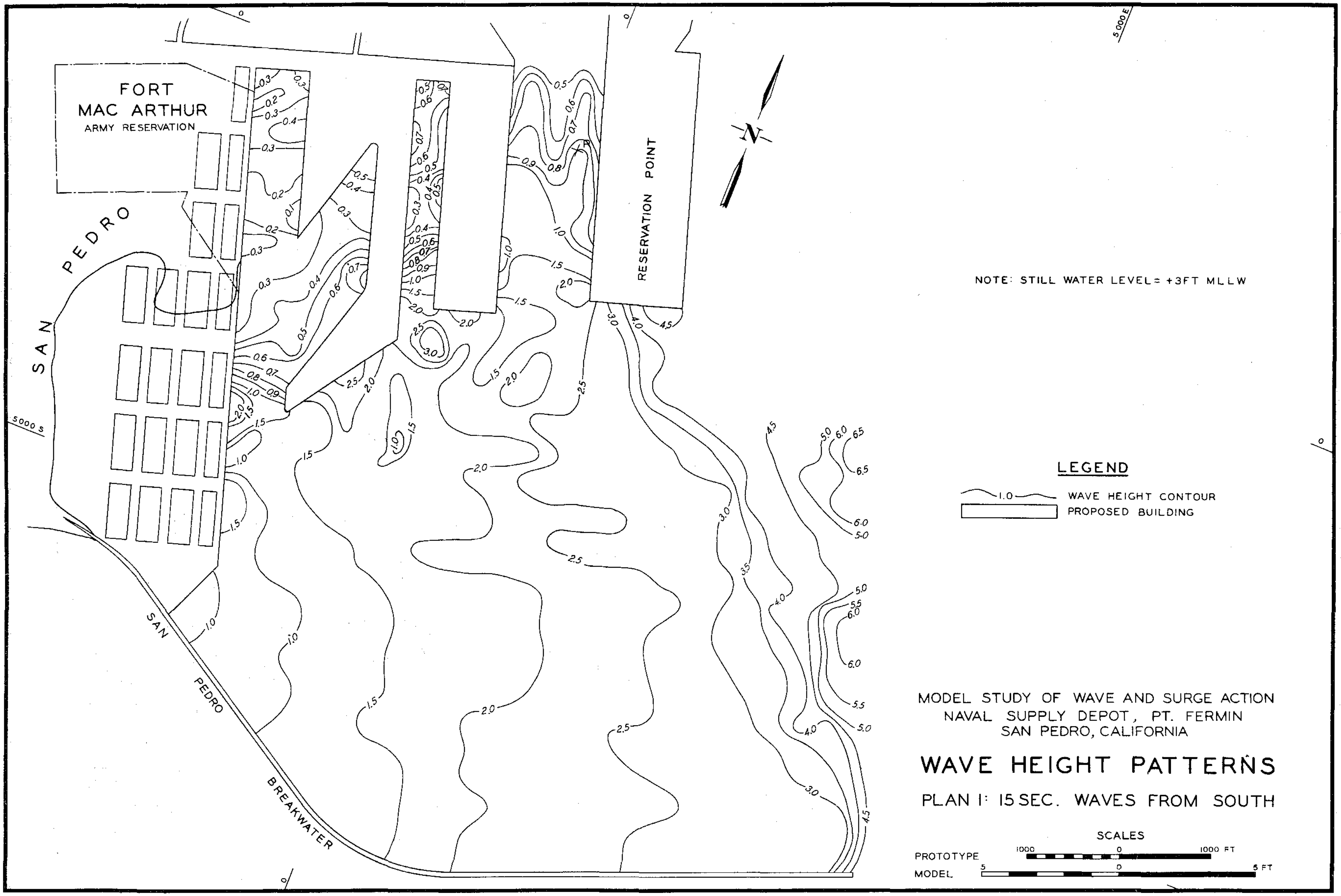

FORT MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
NOTE: STILL WATER LEVEL = +3 FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
PLAN 1: 15 SEC. WAVES FROM S22½° W
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

PLATE 9

PLATE 10


FORT
MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
PLAN I: 15 SEC. WAVES FROM SOUTH
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

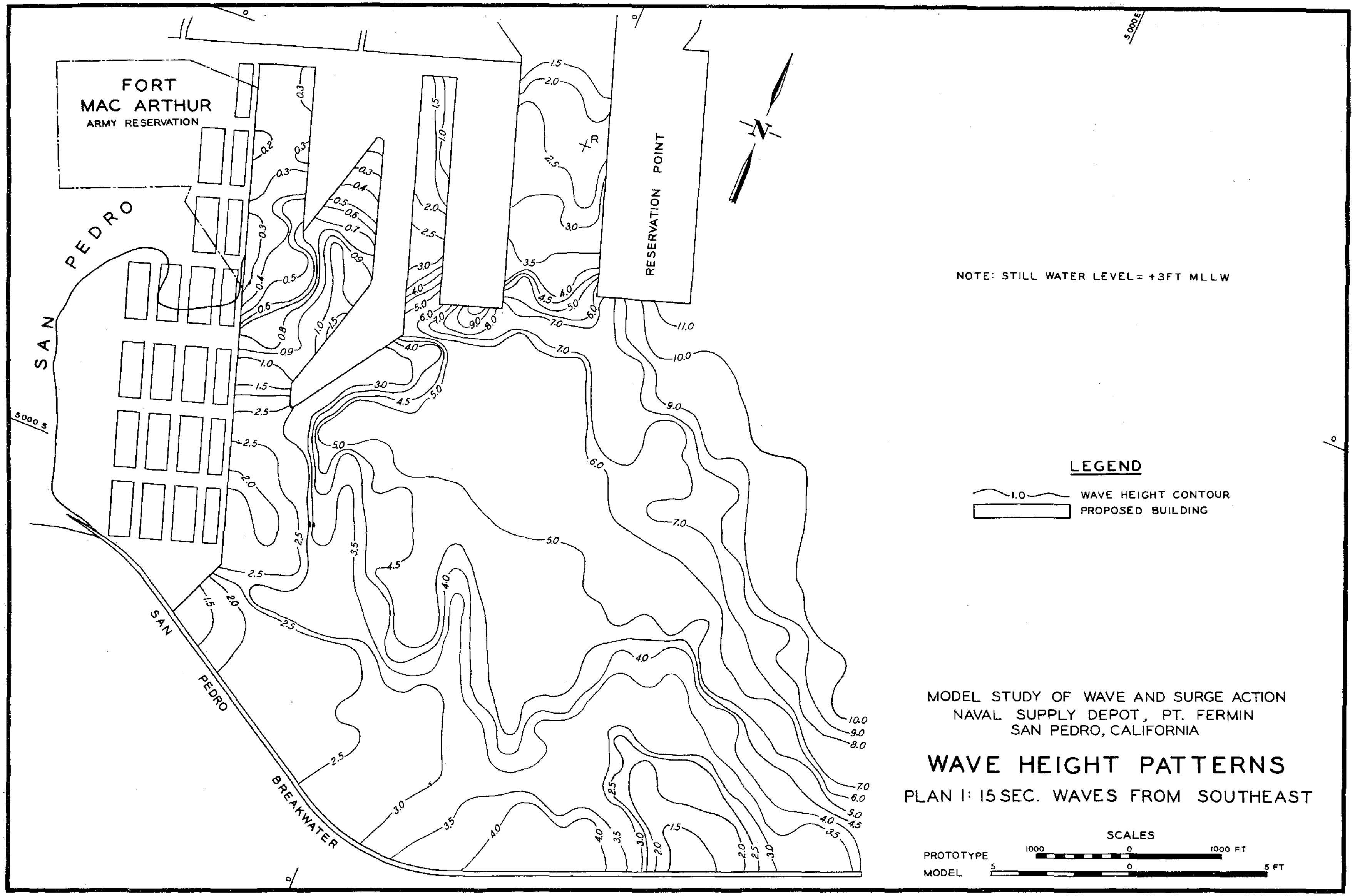
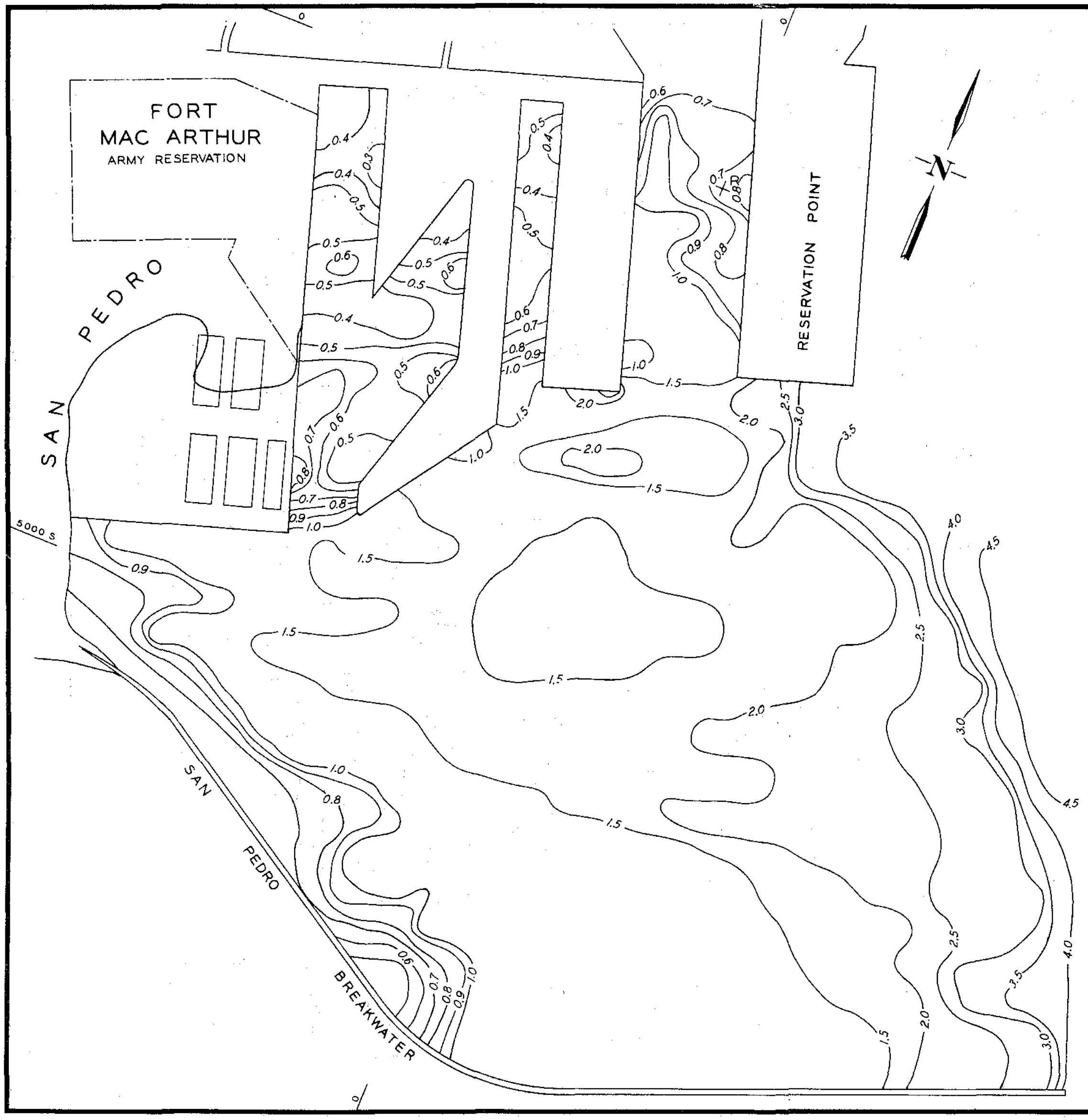

FORT MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
NOTE: STILL WATER LEVEL= +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
PLAN I: 15 SEC. WAVES FROM SOUTHEAST
SCALES
PROTOTYPE
1000 0 1000 FT
MODEL
5 0 5 FT

PLATE 11

PLATE 12



NOTE: STILL WATER LEVEL= +3FT MLLW

LEGEND

1.0 WAVE HEIGHT CONTOUR

PROPOSED BUILDING

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHT PATTERNS

PLAN 2: 15 SEC. WAVES FROM S22 ½° W

SCALES

PROTOTYPE 1000 0 1000 FT

MODEL 5 0 5 FT

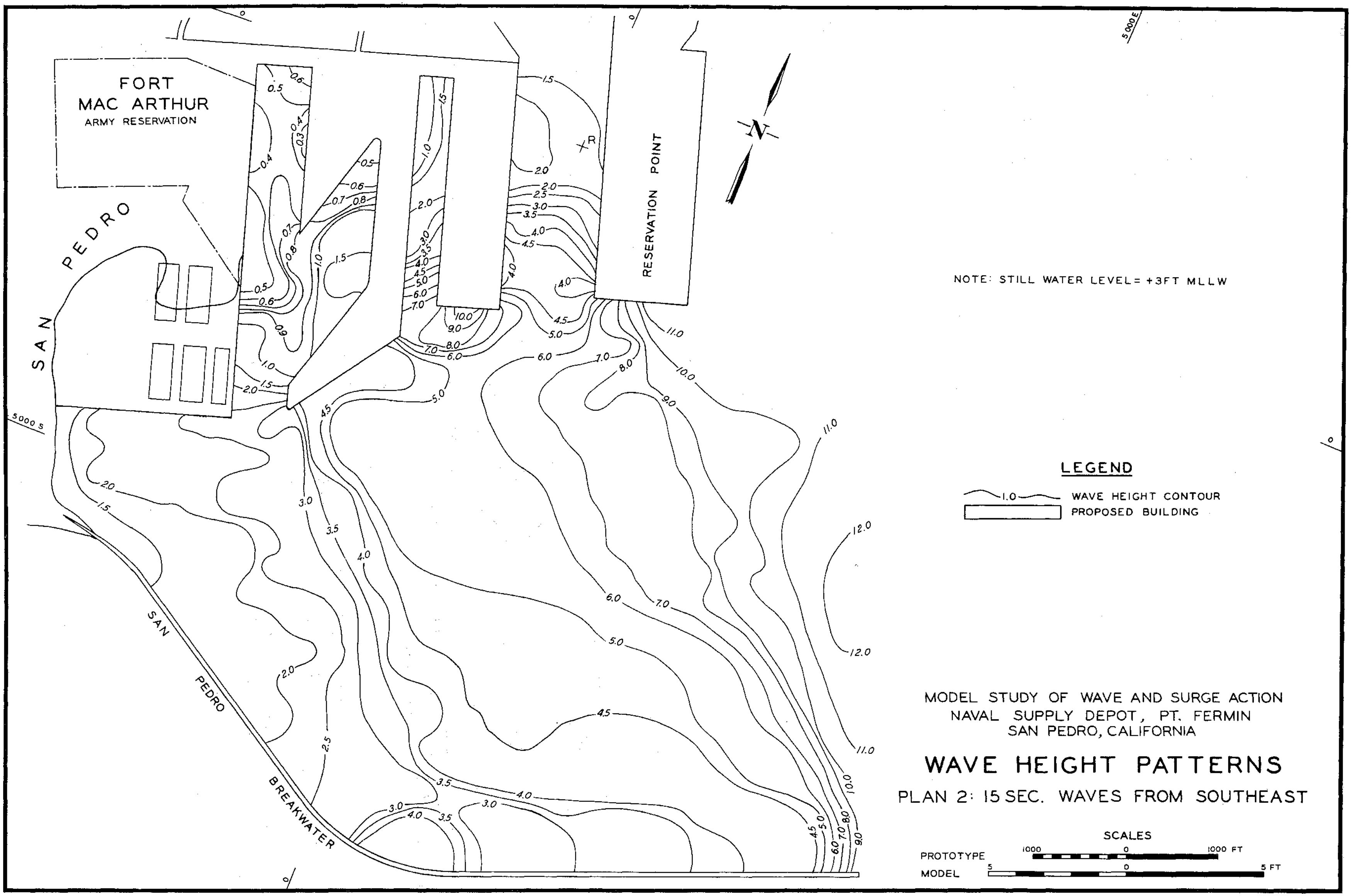
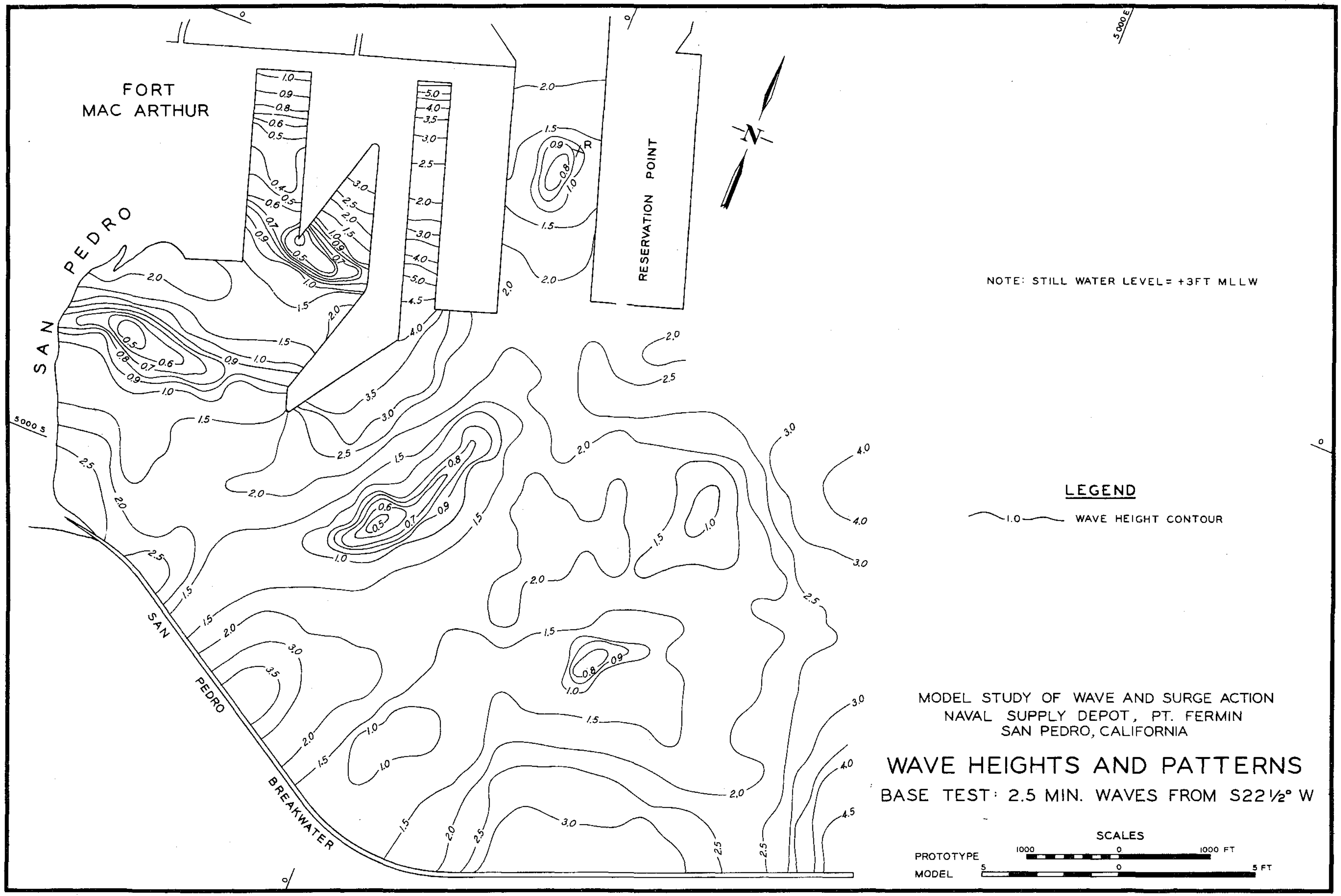

FORT MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
N
NOTE: STILL WATER LEVEL= +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
SAN PEDRO BREAKWATER
5000 S
5000 E
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHT PATTERNS
PLAN 2: 15 SEC. WAVES FROM SOUTHEAST
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

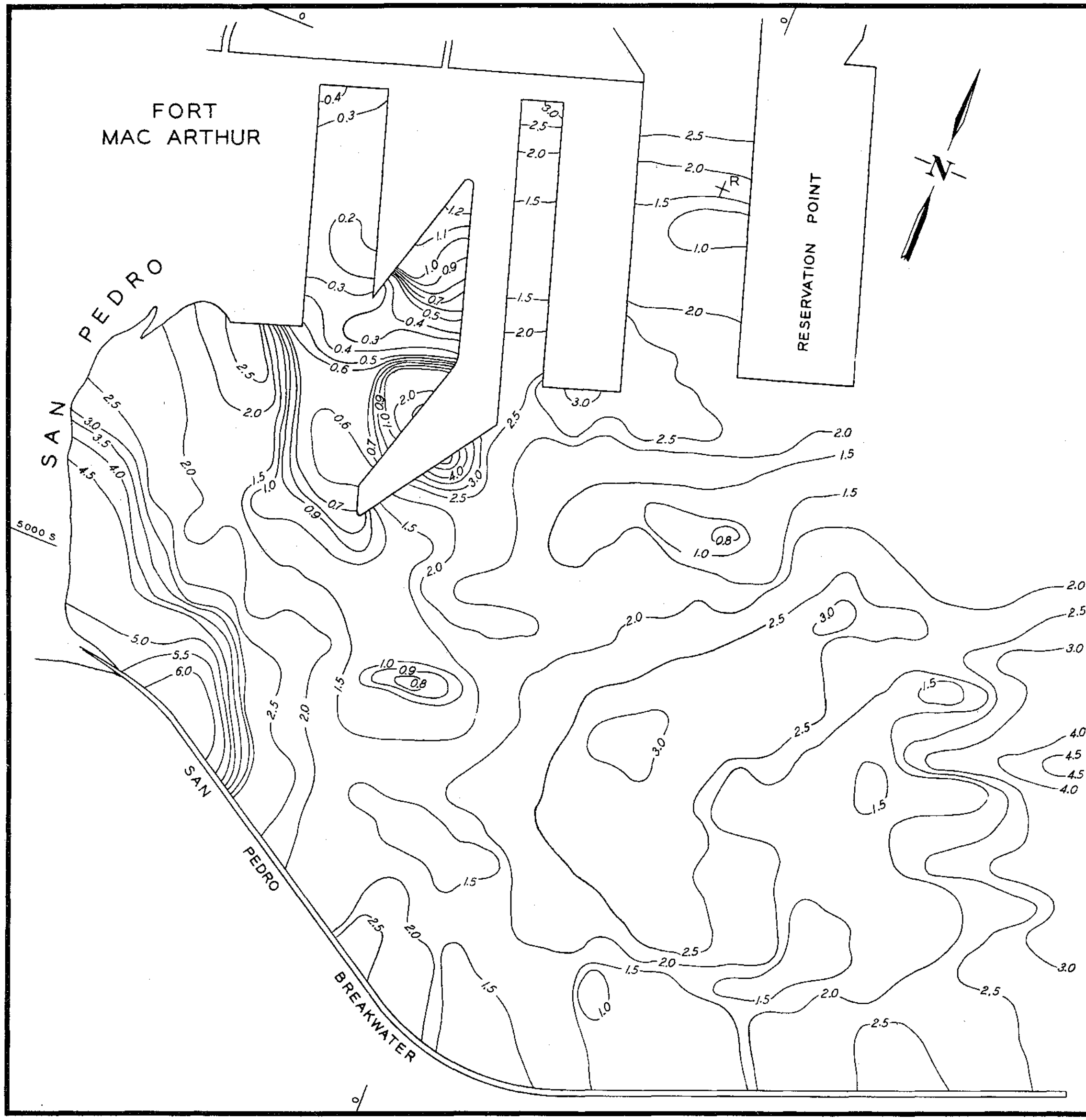
PLATE 13



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS

BASE TEST: 2.5 MIN. WAVES FROM S22½° W



NOTE: STILL WATER LEVEL = +3 FT MLLW

LEGEND

1.0 WAVE HEIGHT CONTOUR

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS

BASE TEST: 2.5 MIN. WAVES FROM SOUTH

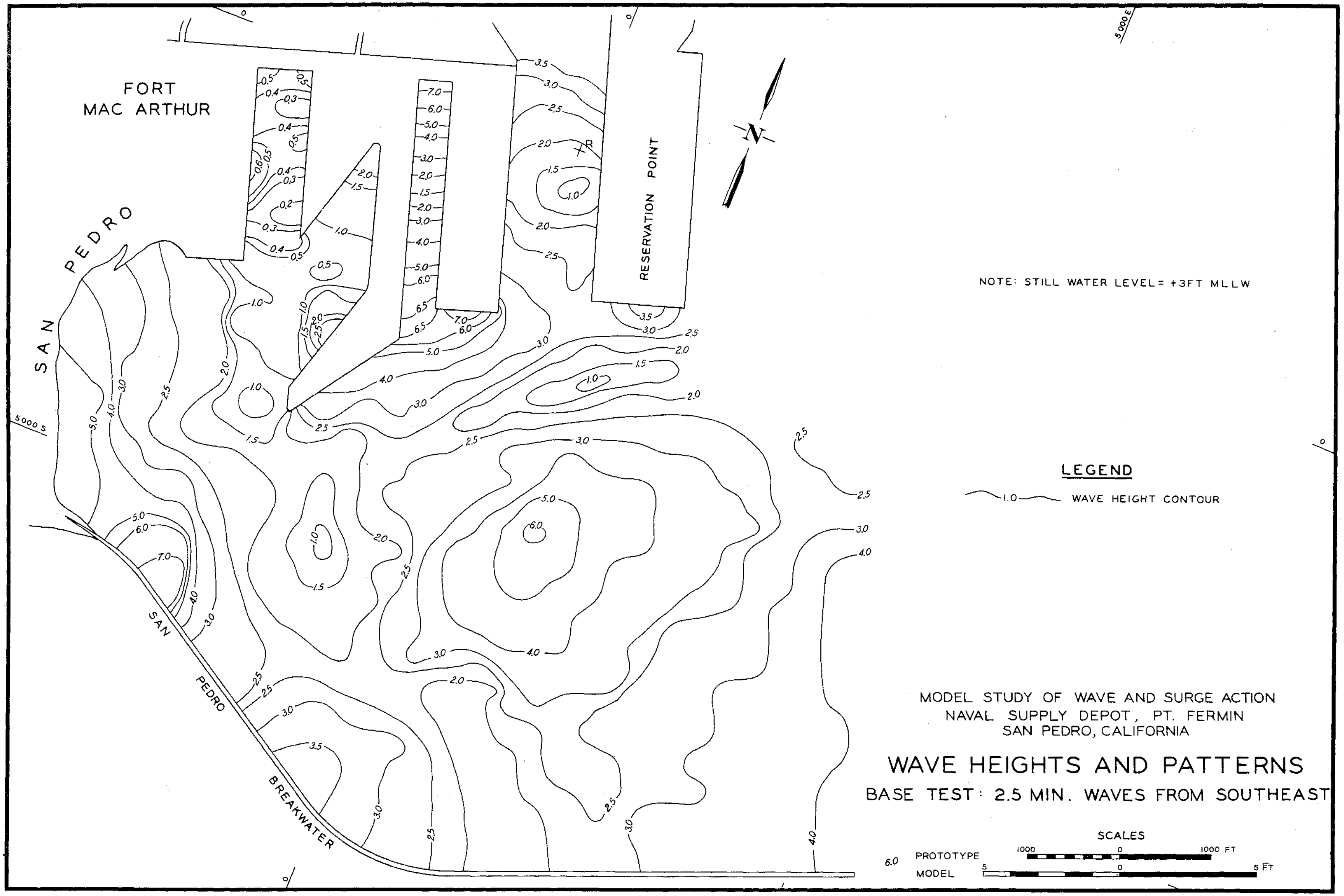
SCALES

PROTOTYPE 1000 0 1000 FT

MODEL 5 0 5 FT

PLATE 15

PLATE 16



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS

BASE TEST: 2.5 MIN. WAVES FROM SOUTHEAST

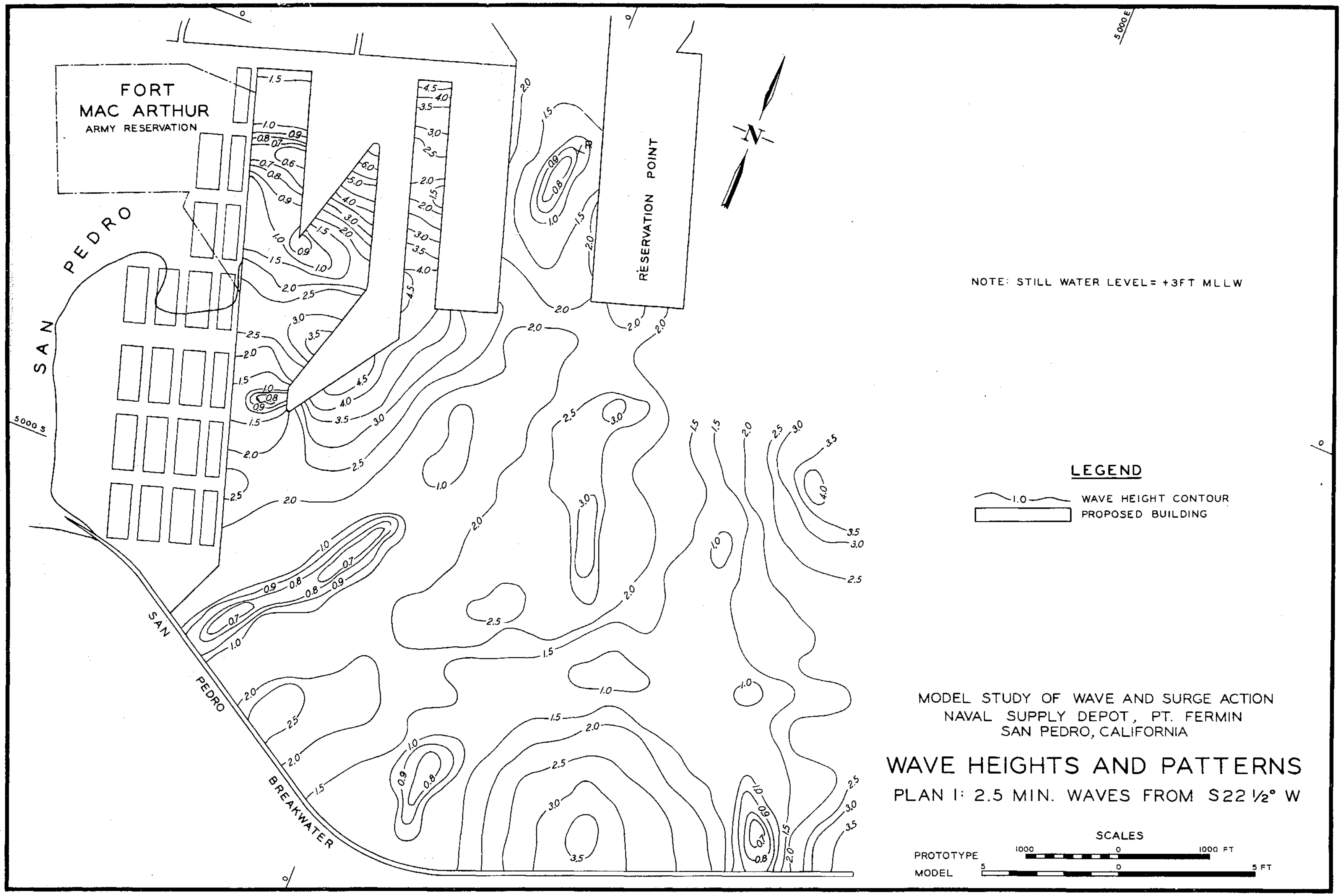
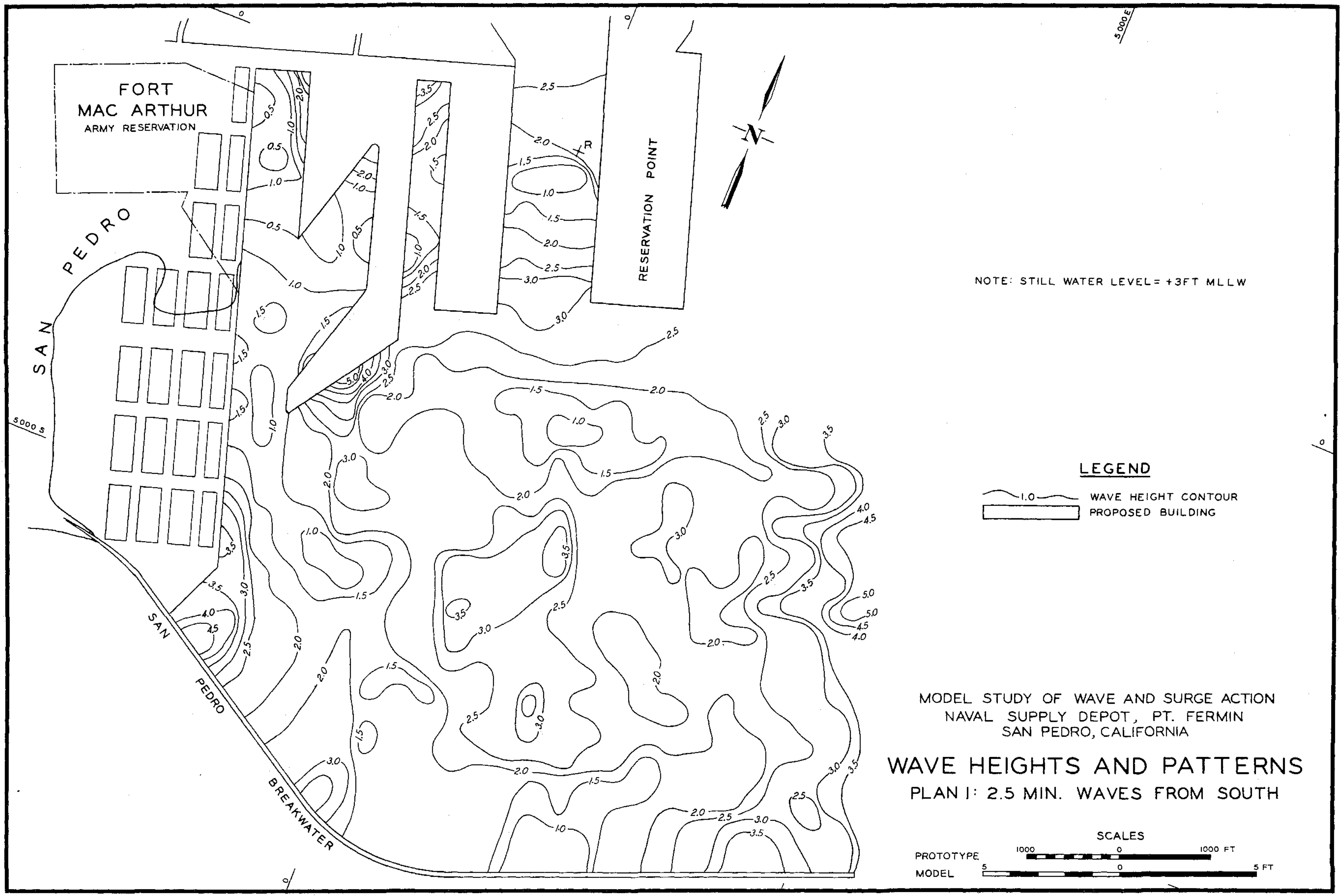
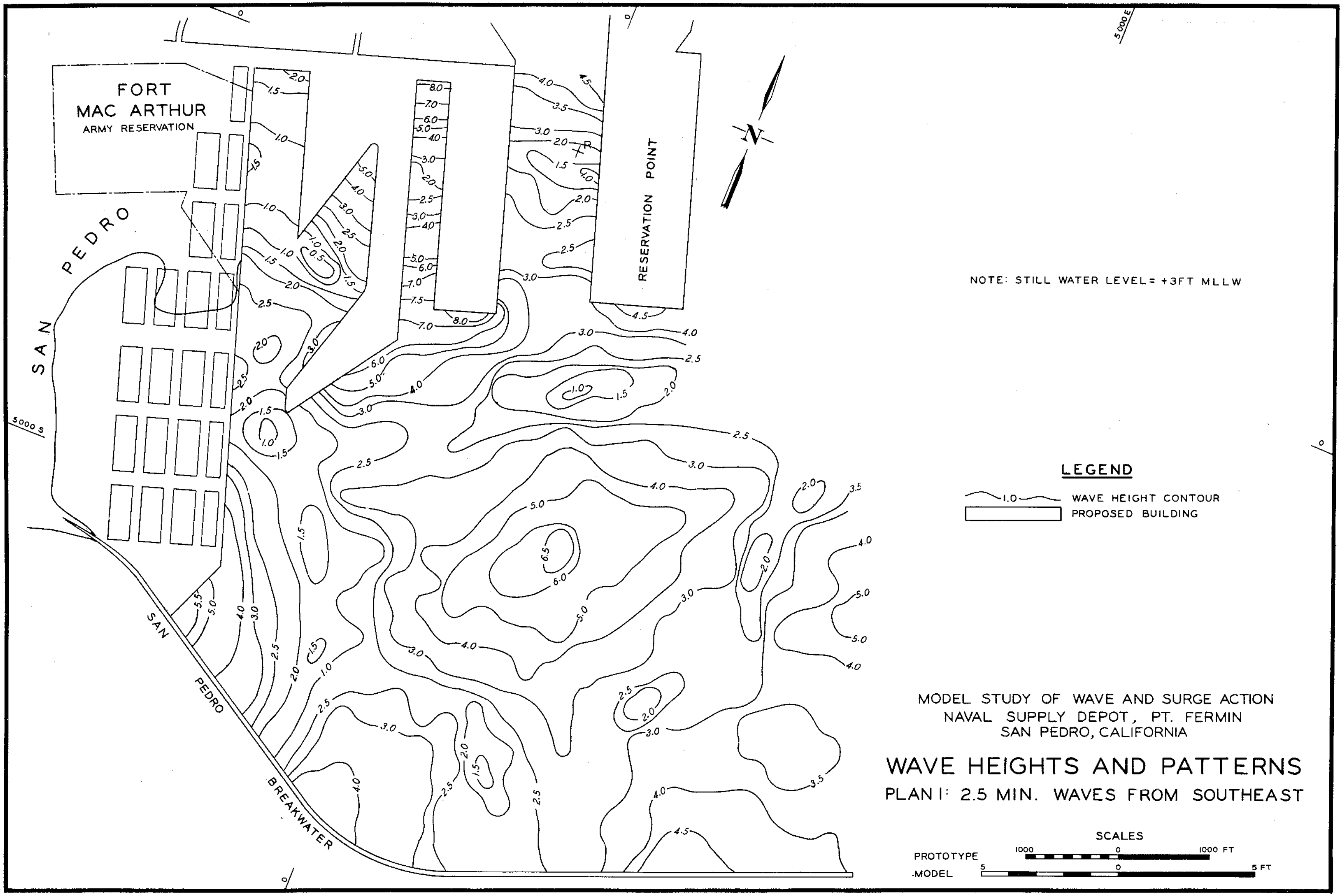

FORT MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
5000 S
5000 E
NOTE: STILL WATER LEVEL = +3 FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
PLAN I: 2.5 MIN. WAVES FROM S22 1/2° W
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

PLATE 17

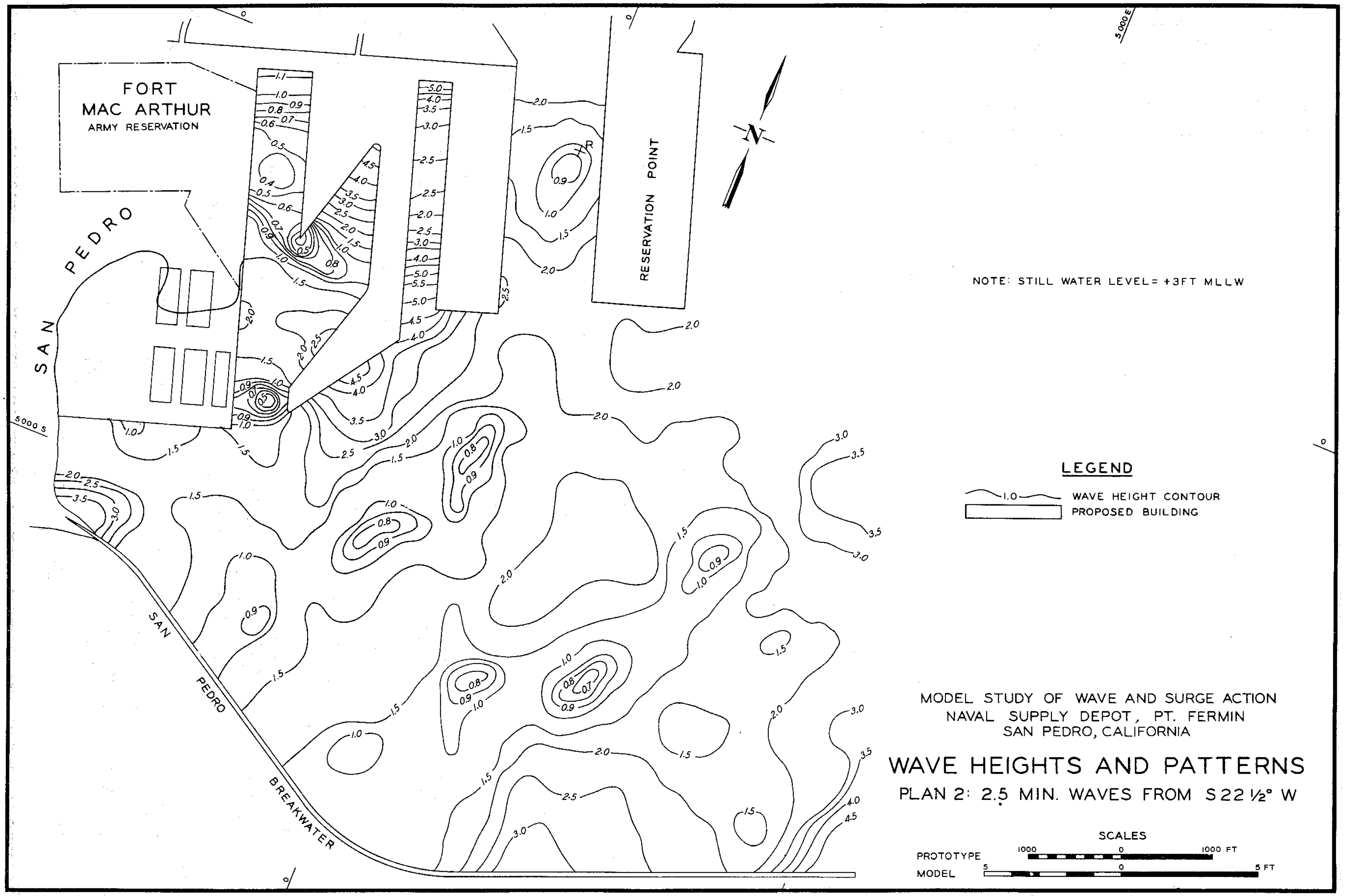
PLATE 18


FORT
MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
5000 S
5,000 E
R
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
PLAN I: 2.5 MIN. WAVES FROM SOUTH
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS
PLAN I: 2.5 MIN. WAVES FROM SOUTHEAST


FORT
MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
NOTE: STILL WATER LEVEL = +3 FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
PLAN 2: 2.5 MIN. WAVES FROM S 22 1/2° W
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

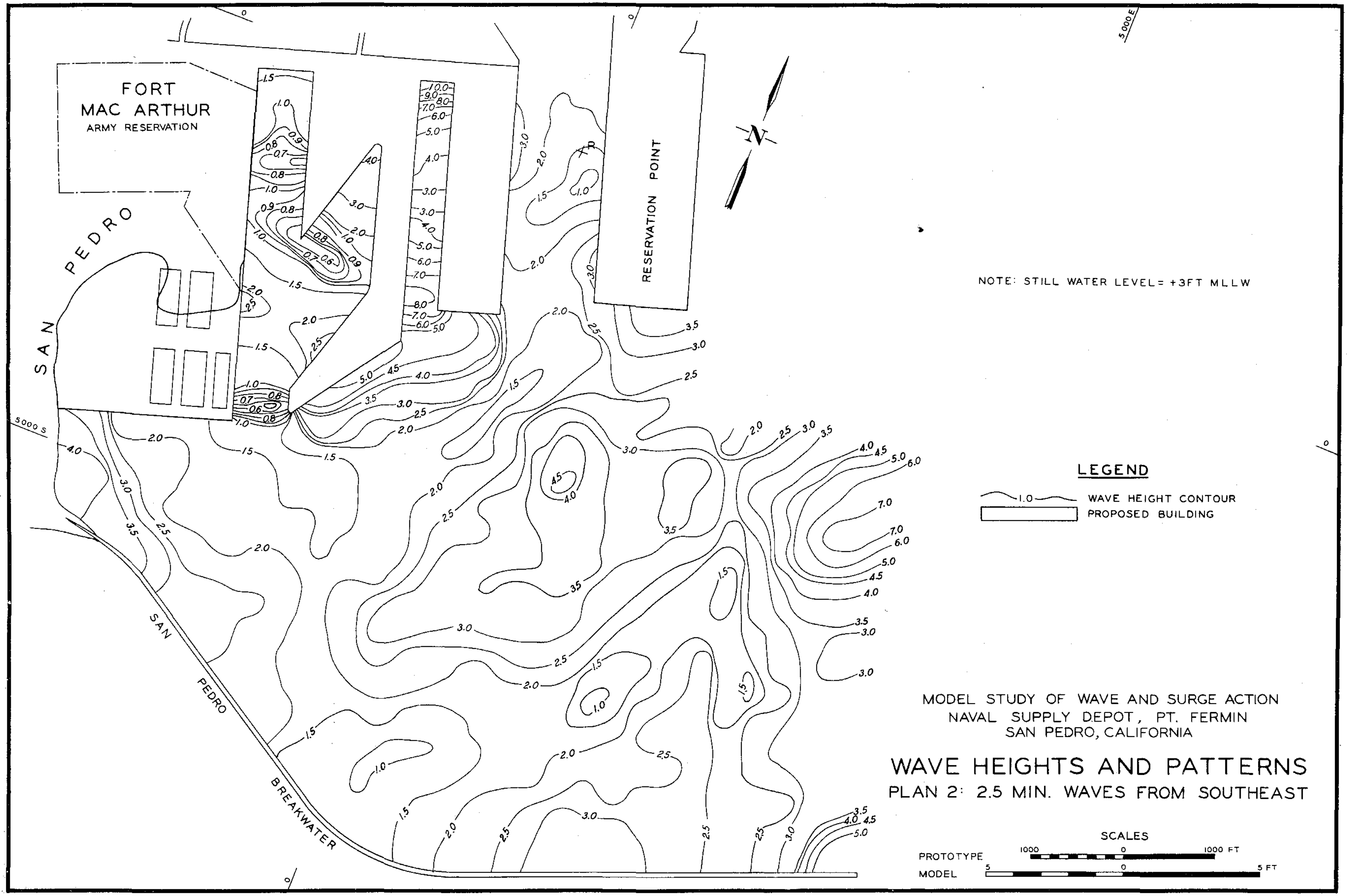
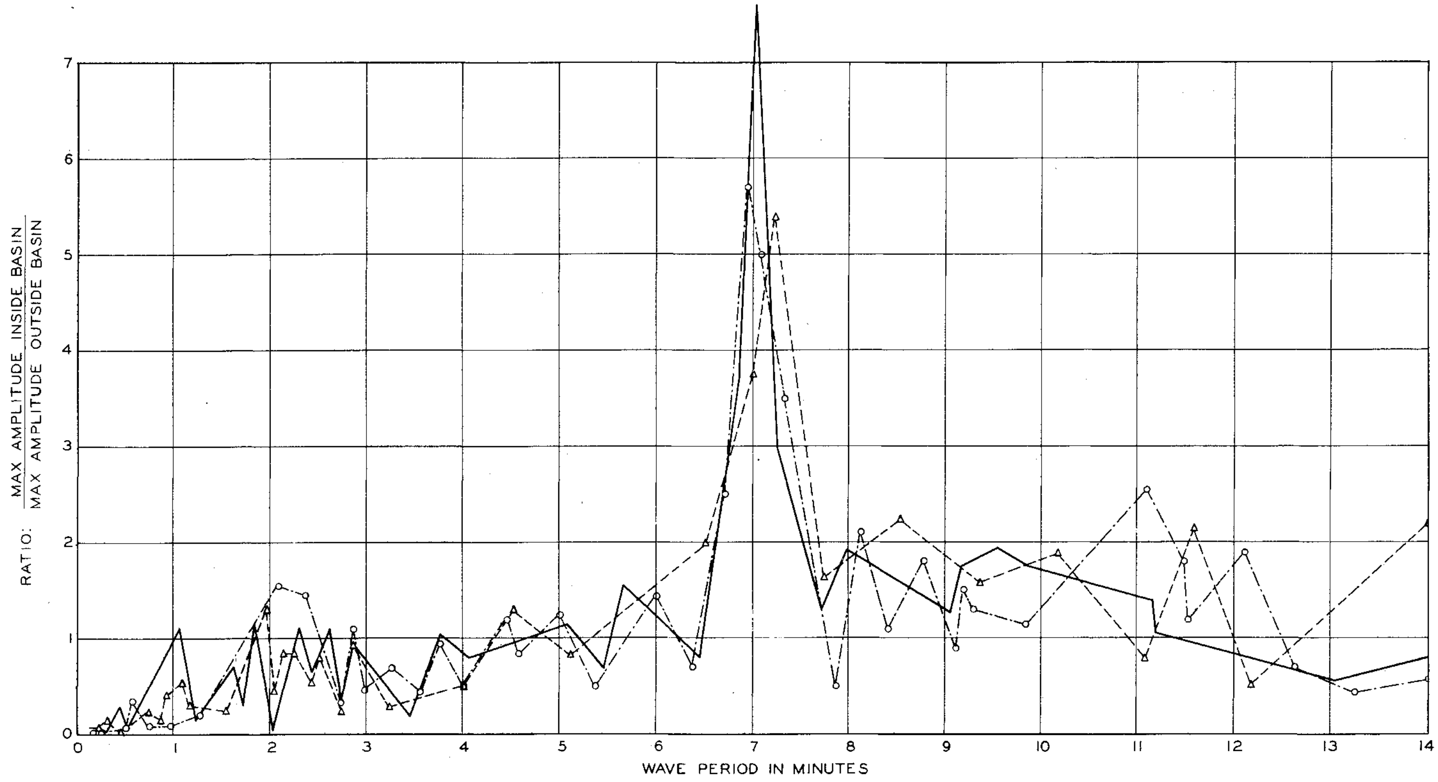

FORT MAC ARTHUR
ARMY RESERVATION
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
5000 S
5000 E
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
PROPOSED BUILDING
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
PLAN 2: 2.5 MIN. WAVES FROM SOUTHEAST
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

PLATE 21



LEGEND

BASE TEST

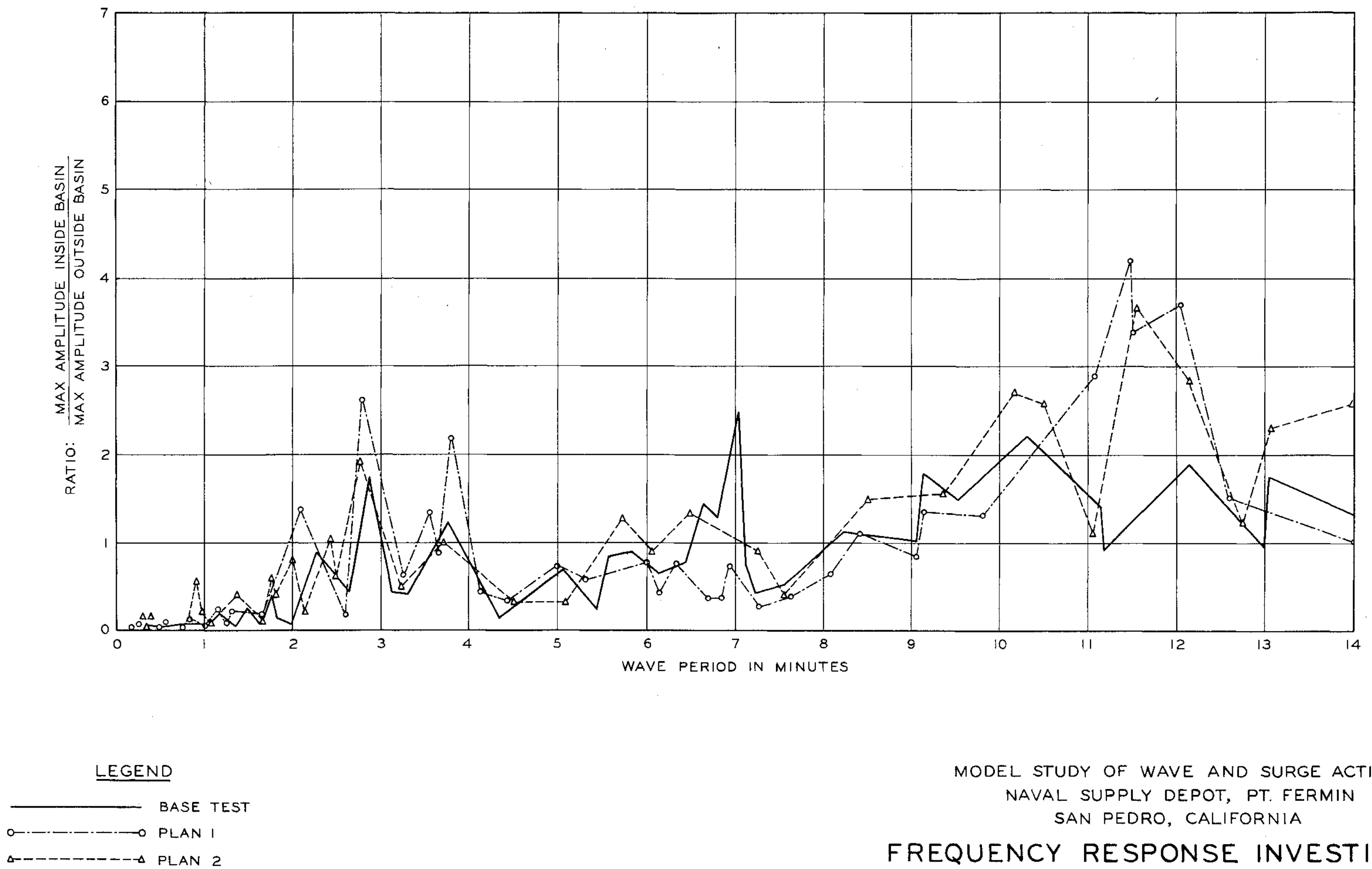
PLAN 1

PLAN 2

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

FREQUENCY RESPONSE INVESTIGATION
EAST CHANNEL

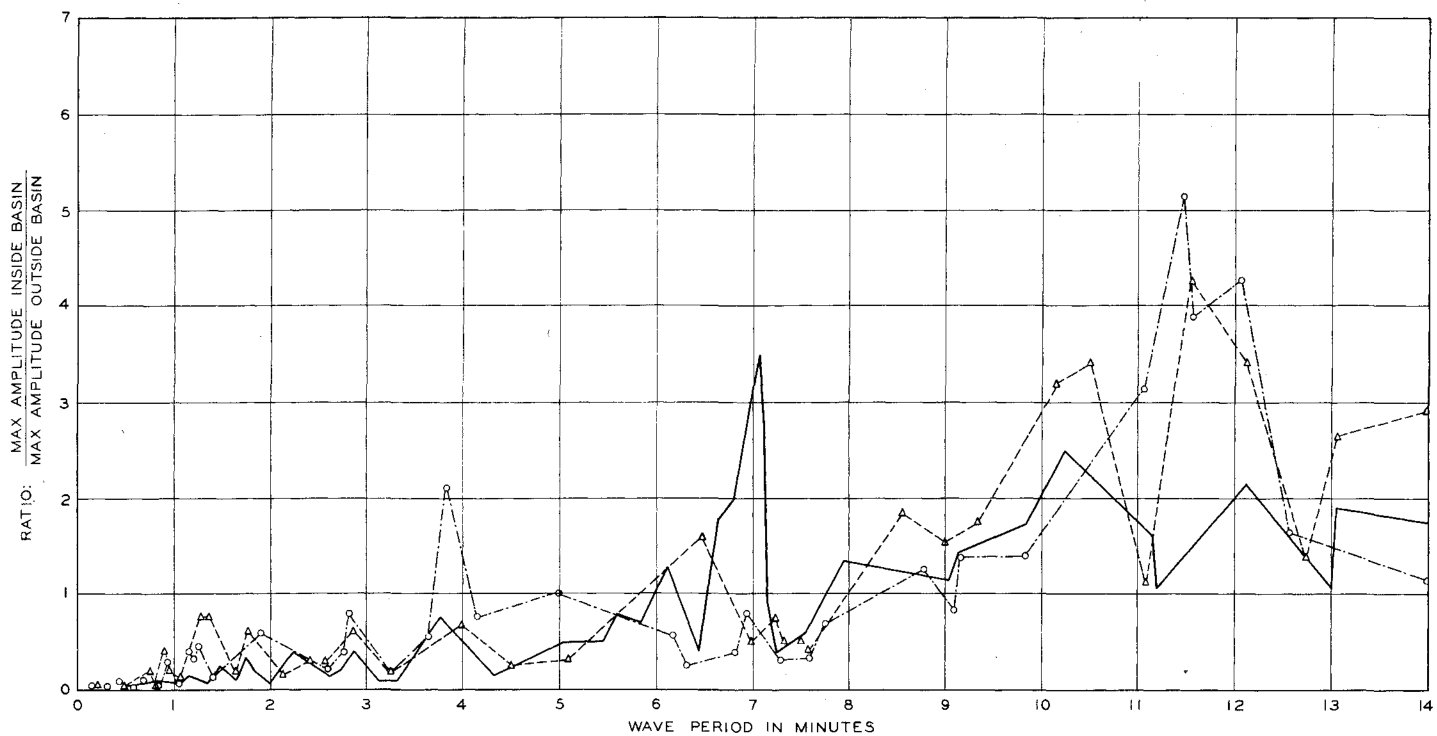
(BASE TEST, PLAN 1, AND PLAN 2)



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

FREQUENCY RESPONSE INVESTIGATION
WATCHORN BASIN

(BASE TEST, PLAN 1, AND PLAN 2)



LEGEND

BASE TEST

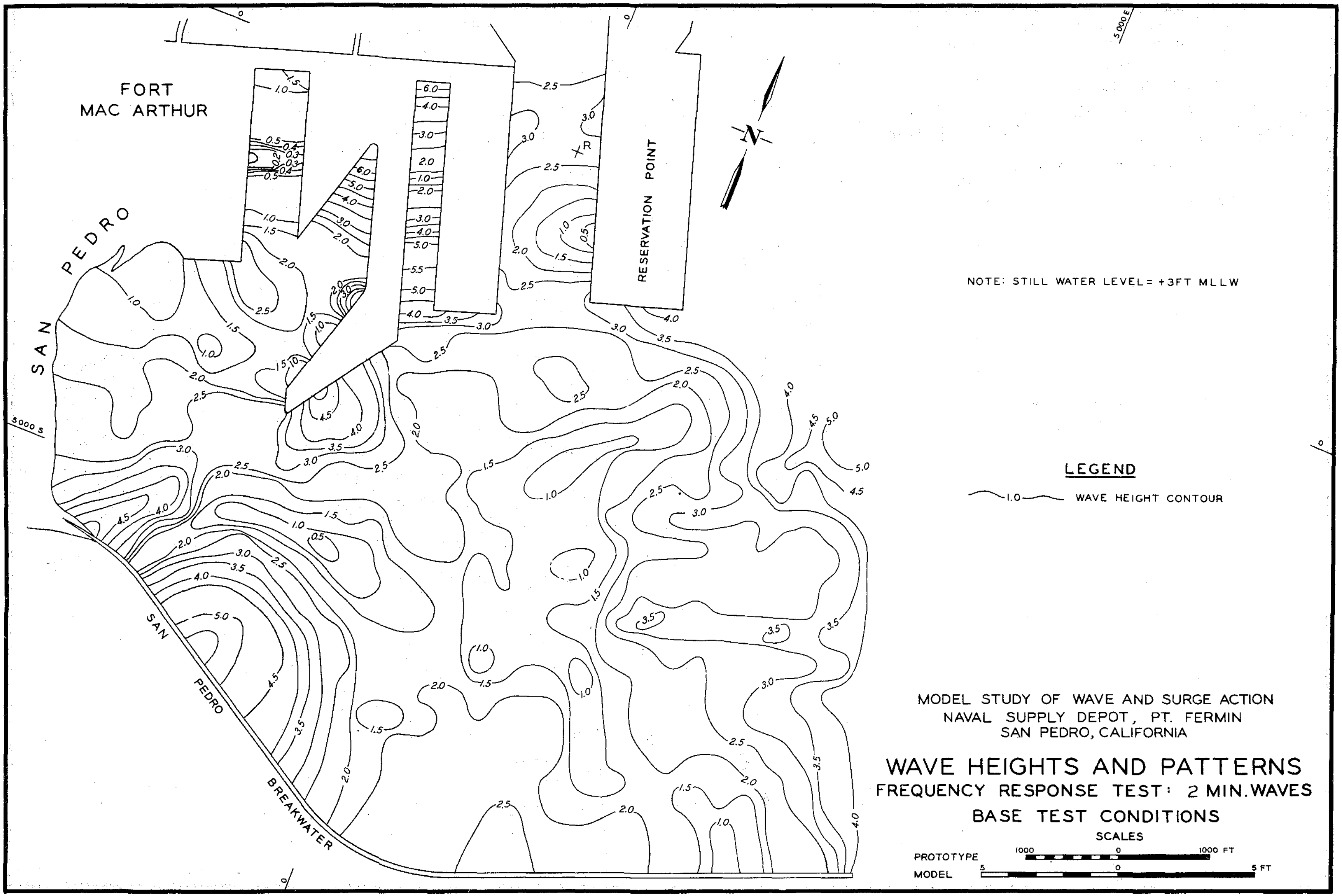
PLAN 1

PLAN 2

MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

FREQUENCY RESPONSE INVESTIGATION
WEST CHANNEL

(BASE TEST, PLAN 1, AND PLAN 2)

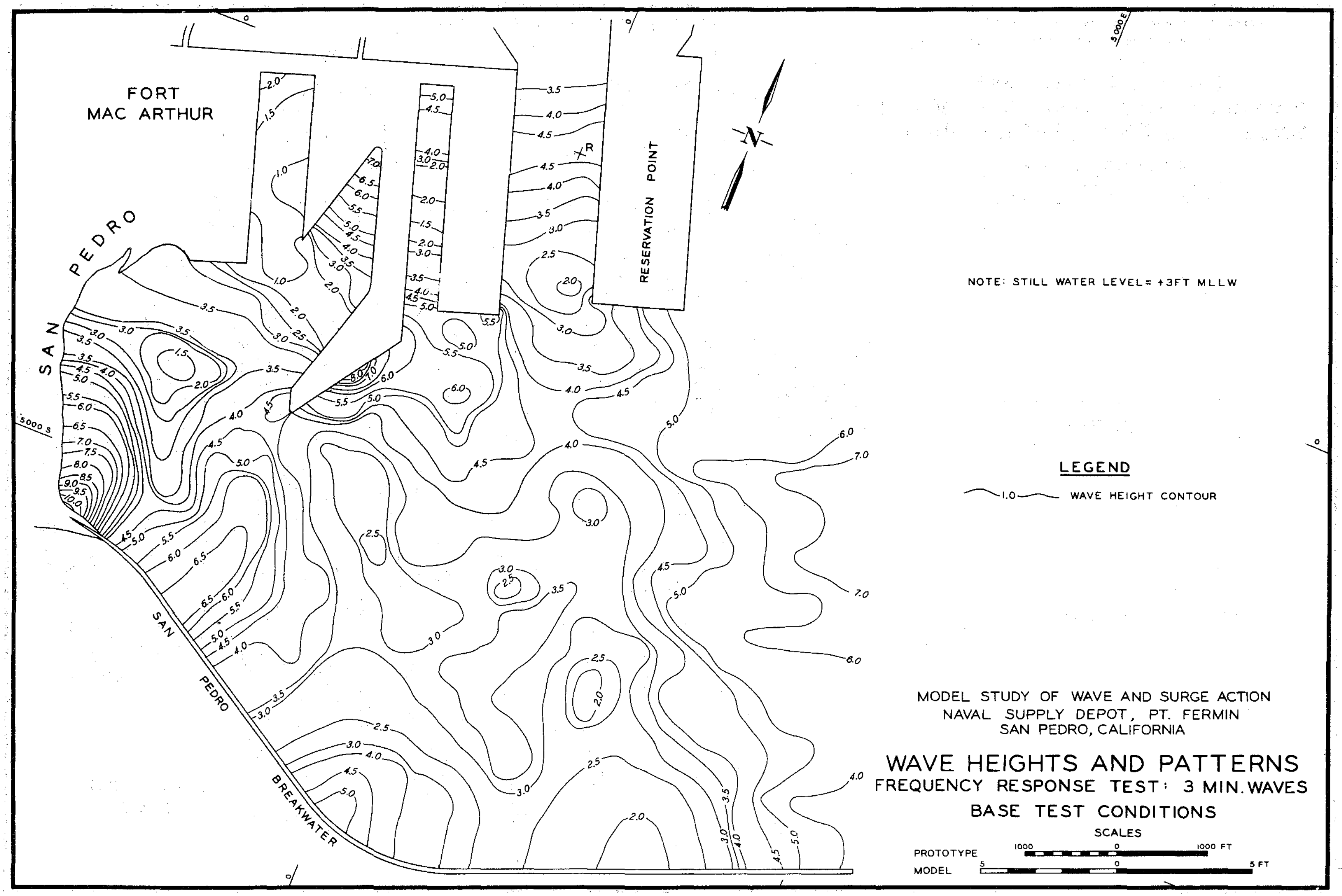


MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 2 MIN. WAVES
BASE TEST CONDITIONS

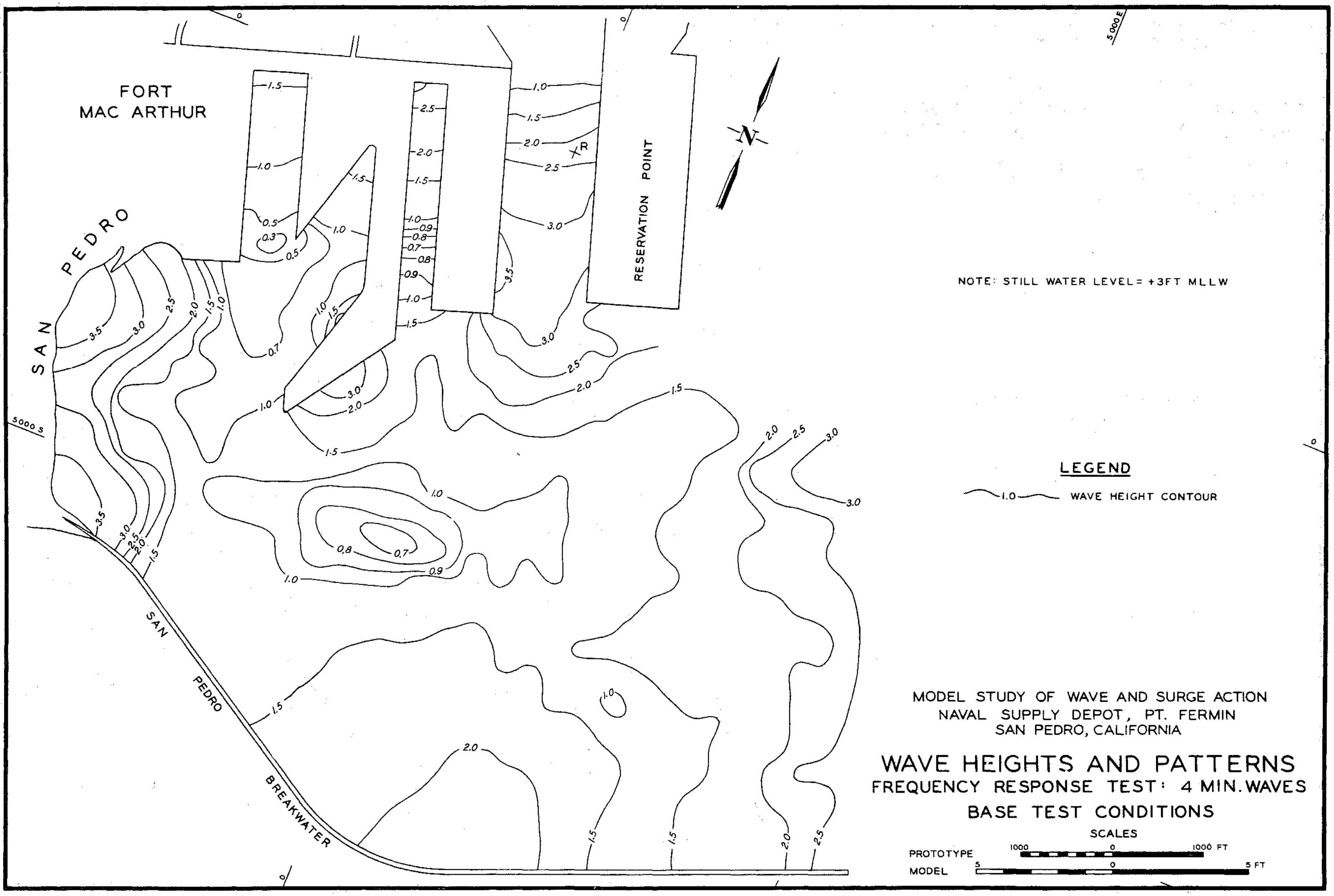
PLATE 25

PLATE 26



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 3 MIN. WAVES
BASE TEST CONDITIONS



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

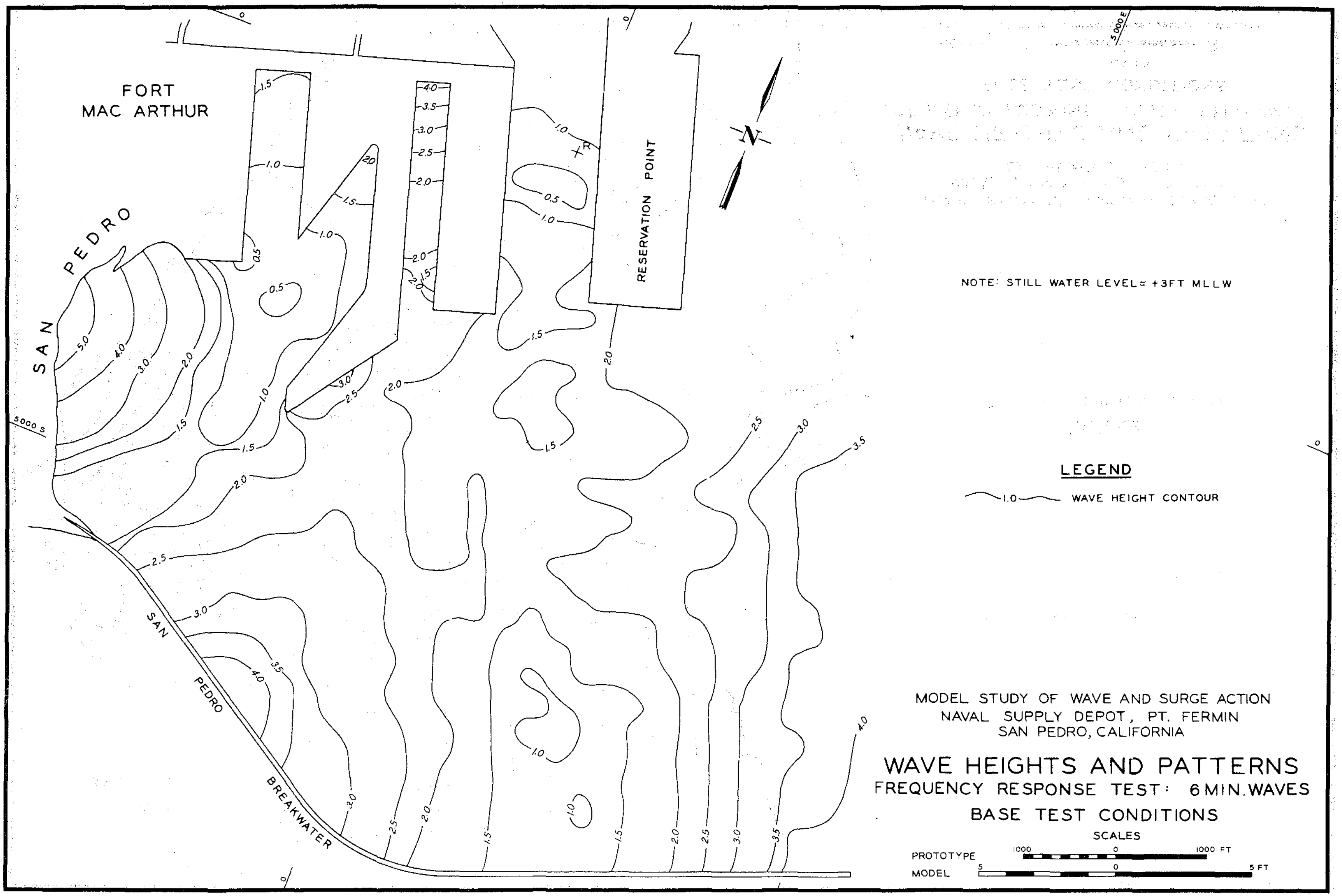
WAVE HEIGHTS AND PATTERNS

FREQUENCY RESPONSE TEST: 4 MIN. WAVES

BASE TEST CONDITIONS

PLATE 27

PLATE 28


FORT MAC ARTHUR
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
NOTE: STILL WATER LEVEL = +3 FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
5000 S
5000 E
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 6 MIN. WAVES
BASE TEST CONDITIONS
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

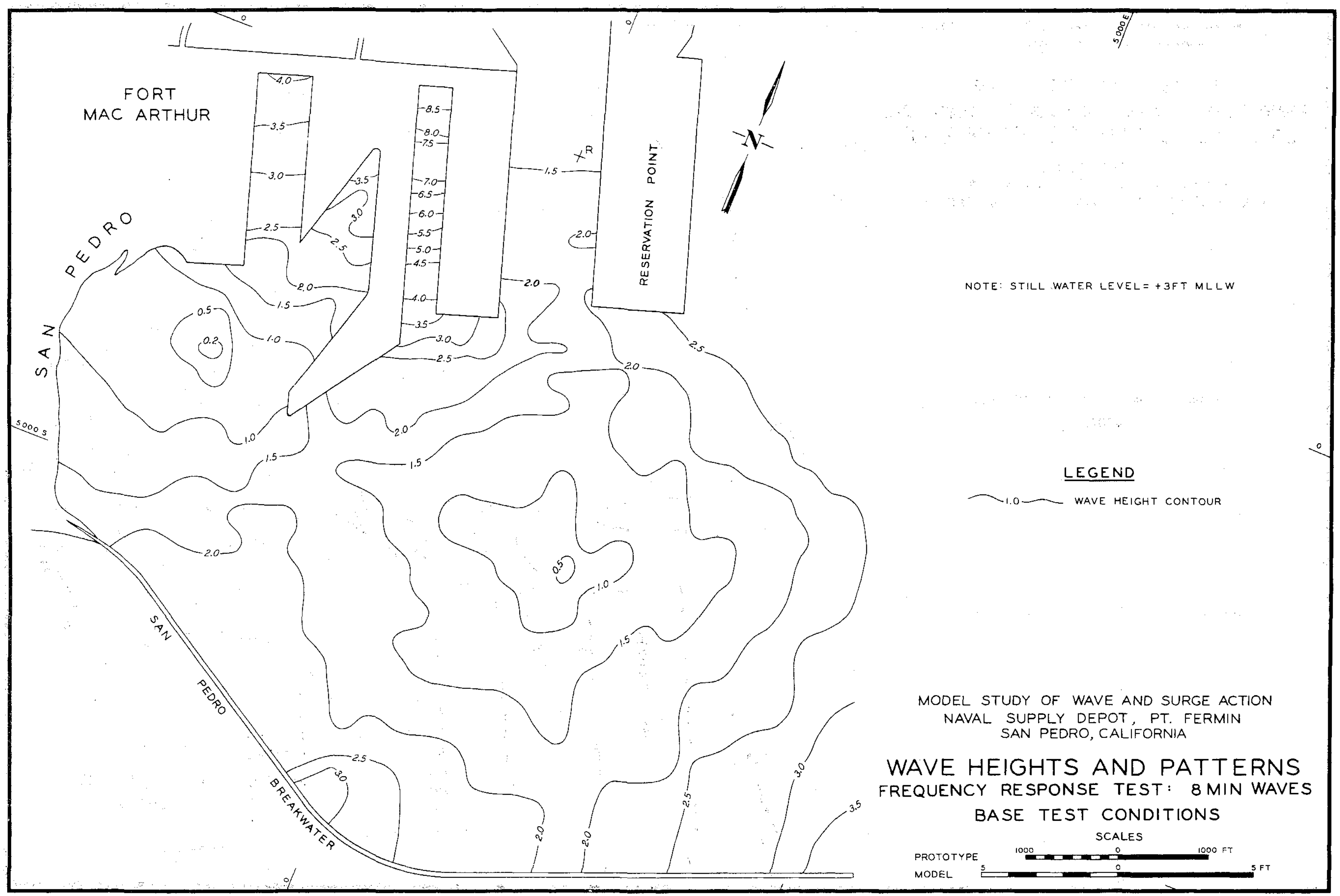
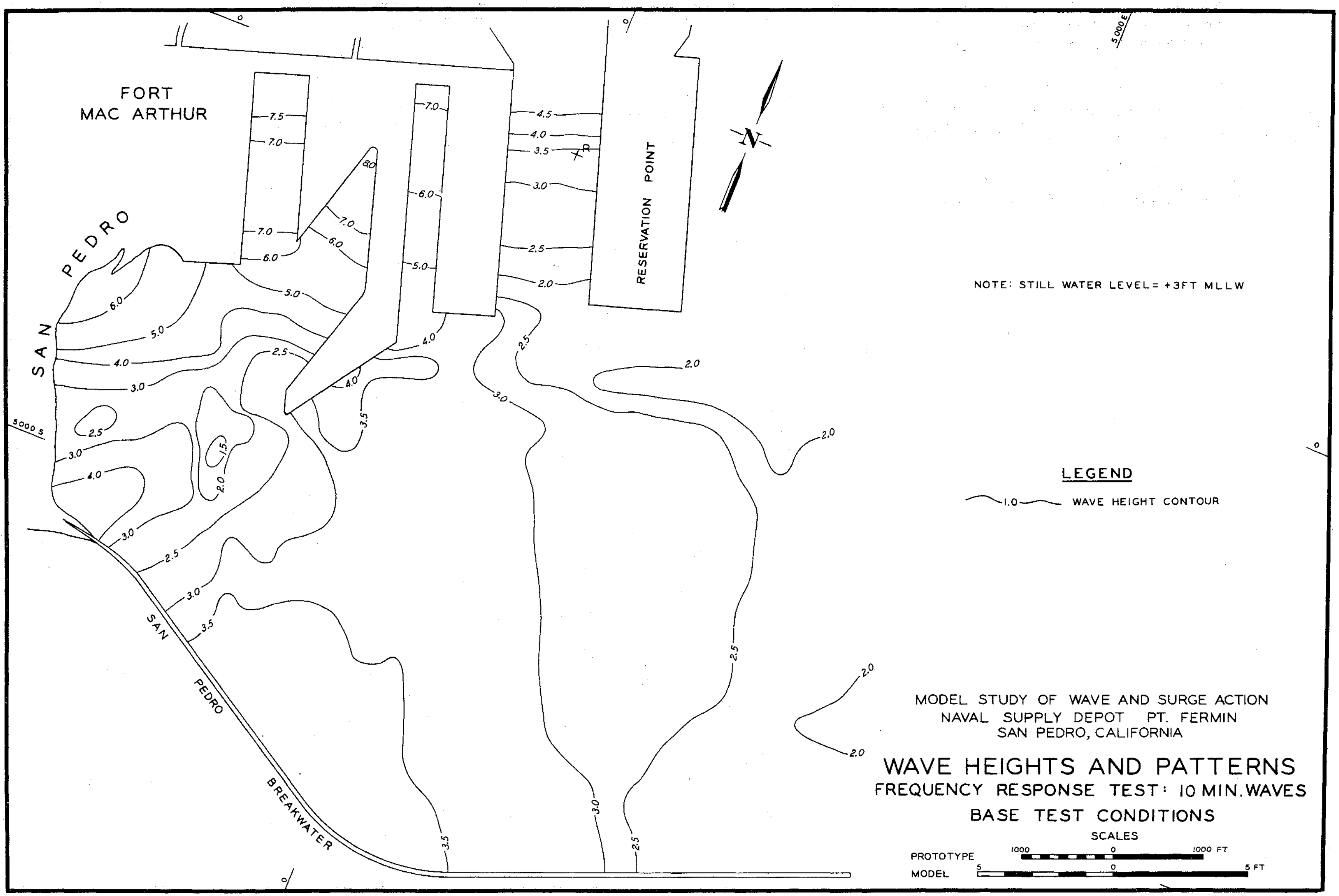
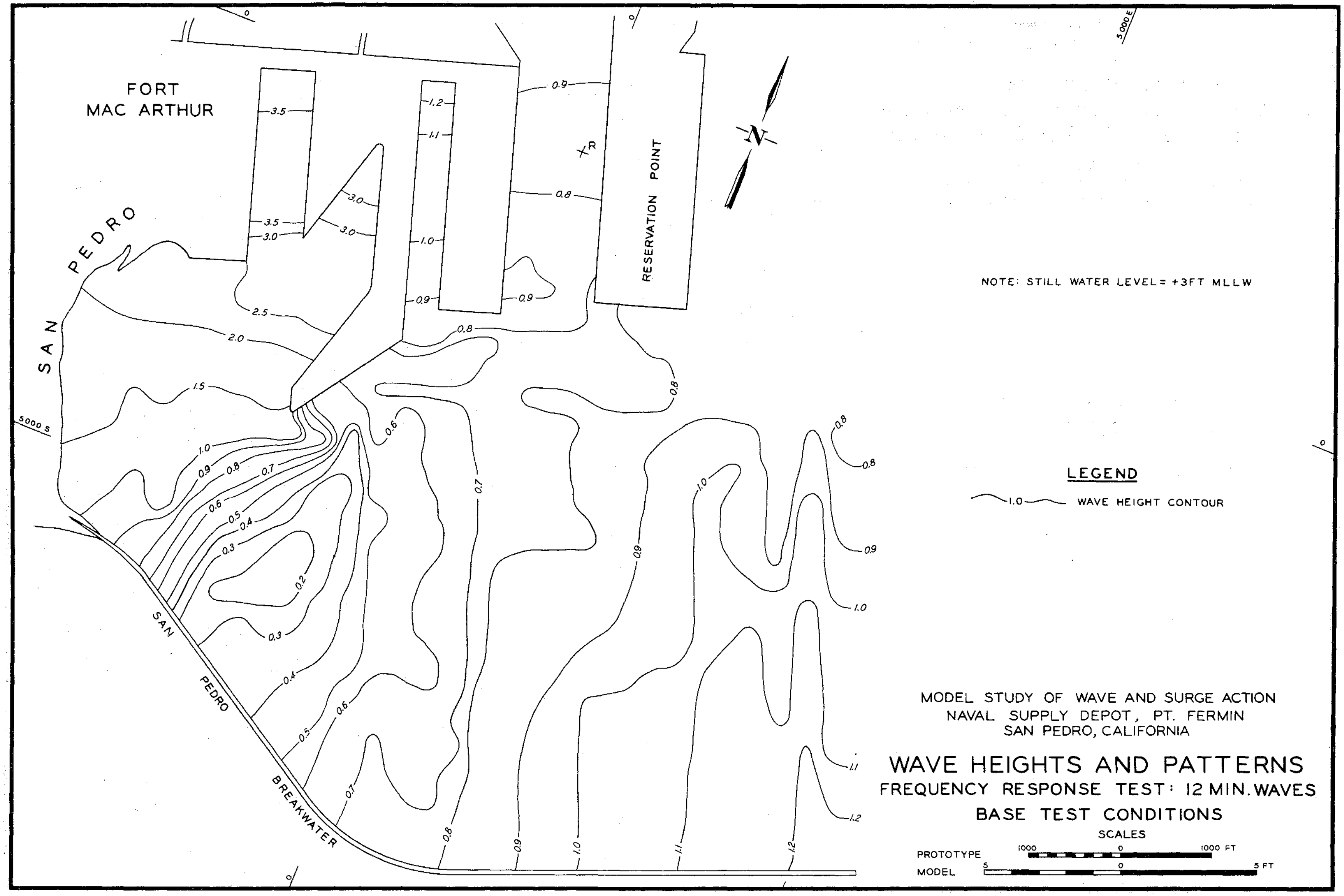

FORT MAC ARTHUR
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
NOTE: STILL WATER LEVEL = +3 FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 8 MIN WAVES
BASE TEST CONDITIONS
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT
5000 S
5000 E

PLATE 29


FORT MAC ARTHUR
SAN PEDRO
RESERVATION POINT
SAN PEDRO BREAKWATER
N
5000 S
5000 E
NOTE: STILL WATER LEVEL = +3FT MLLW
LEGEND
1.0 WAVE HEIGHT CONTOUR
MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT PT. FERMIN
SAN PEDRO, CALIFORNIA
WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 10 MIN. WAVES
BASE TEST CONDITIONS
SCALES
PROTOTYPE 1000 0 1000 FT
MODEL 5 0 5 FT

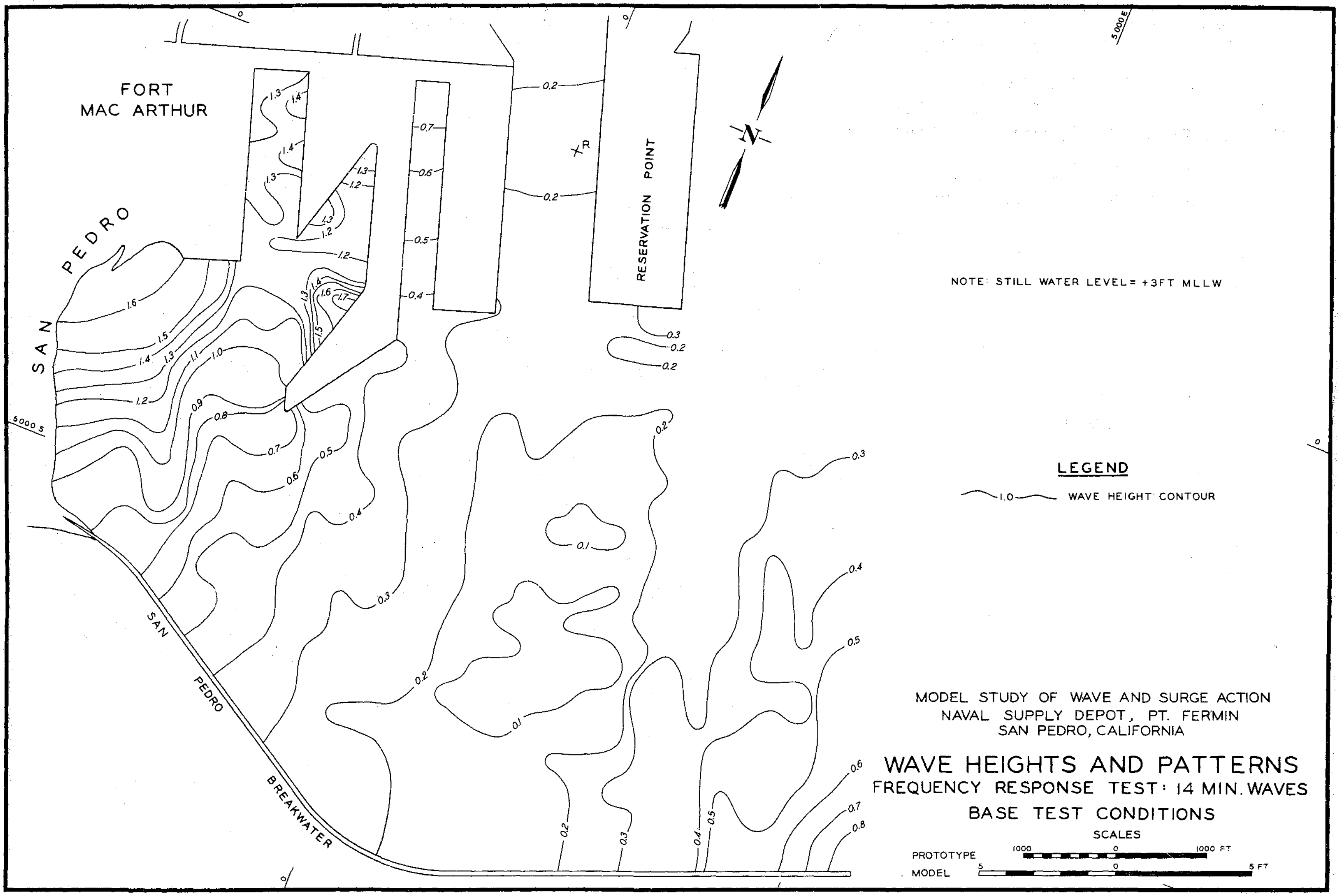


MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 12 MIN. WAVES
BASE TEST CONDITIONS

PLATE 31

PLATE 32



MODEL STUDY OF WAVE AND SURGE ACTION
NAVAL SUPPLY DEPOT, PT. FERMIN
SAN PEDRO, CALIFORNIA

WAVE HEIGHTS AND PATTERNS
FREQUENCY RESPONSE TEST: 14 MIN. WAVES
BASE TEST CONDITIONS

APPENDIX

APPENDIX

WAVE AND SURGE ACTION IN LOS ANGELES HARBOR

(Extracts from informal letter by the late Mr. D. E. Hughes, dated April 28, 1924)

". . . Since writing in 1922 on surge in Los Angeles outer harbor I have thought and seen a little more. Every morning while dressing I see whether vessels at anchor behind the breakwater have that small and slow to and fro movement indicative of the presence of surge.

". . . Now just what is surge? Whoever has carried a plate of soup or a basin of water has seen it. You, or rather your mules felt it when hauling a part-full water wagon, before you put in cross walls to prevent it. It is not an ordinary wave motion at all, but the simpler thing - a mere oscillation of the whole body of water throughout its depth from side to side or end to end of the vessel, - something akin to the vibration of a pendulum, and as easily calculated if the vessel is of mathematical shape like a trough or canal or harbor slip.

"But what makes it? The jerky walk or a rutty road are enough for the soup or water wagon; but something bigger is needed to shake a lake or harbor. Earthquakes of course would do it, but they don't happen often enough to write about.

"When a wind stops after blowing long enough to lower the water at one end of a lake and raise it at the other, the water in returning to its level fails to stop there; but, by virtue of its momentum gained, goes past like a pendulum to the other extreme and thus vibrates back and forth for hours. Were it not for the friction of the air above and the bed below, and maybe a little viscidity or stickiness of the water, it

would never stop unless we knock out a side of the basin so a fraction of each flow can escape laterally never to return.

"Another cause in long lakes is a temporary inequality of atmospheric pressure on the two ends, which happens oftenest near mountains that restrict the paths of upper air currents which have their effects on barometers, or pressure in quieter air below.

"The first painstaking observations of such oscillations in a lake were made some 50 years ago by Dr. Forel on Lake Geneva, who found that its period, or time between successive high waters at the end of the lake was 73 minutes in case of movements lengthwise, and 10 minutes at the side of the lake on occasions when the movement was crosswise. These observations of times agreed very well with calculations of time based on theory together with the known dimensions and depths of the lake.

". . . The physicist can demonstrate that the velocity with which the pulsation, or something, travels the length of the lake or basin and back again is the same as the velocity acquired by a body falling through a distance equal to half the depth of the water. When depths are variable the practice is to take the average; but greater accuracy, if desired, is attained by dividing the length into sections according to depths, and applying the rule to each, and then combining the results.

"Figuring on Los Angeles outer harbor, the average high tide depth of the easterly slip and its prolongation to the breakwater is between 40 and 41 feet, and a body falling half this distance acquires a velocity of about 36 feet per second. Dividing this into twice the length from the end of the slip to the breakwater, say 18,000 feet, gives 500 seconds, or 8 minutes and 20 seconds as the calculated interval between any two

successive high waters at the end of the slip.

"If the course of travel bends, as it is constrained to do by the curved plan of Lake Geneva, the distance becomes longer, say about 11,000 feet to the breakwater light house, and of course the time would be correspondingly longer, or about 10 minutes and 11 seconds; but, though travel if originating at the light house would take a bent course to enter the slip, the return from the slip, and all repetitions from the same first cause, would be along the straight line of the slip and its prolongation, for there are no banks to deflect it.

"Now don't go astray on this so-called velocity of 36 feet per second. It is not the rate at which pressure is transmitted by water when confined as in a pressure pipe, which is more than a hundred times as fast. Nor is it the velocity with which any of the water travels during surge in the outer harbor, which is not a tenth part as fast.

". . . Suppose we push on the end of a horizontal prism of water; if the water cannot get out of the way laterally nor upwards the push will be felt at the far end as soon as sound can travel there through water which goes over 4,000 feet per second; but when the cover is off, our push only squashes the first water upwards; then it, on account of being then higher, pushes the next, and so on; and the considerable time it takes each successive installment of water to hump its back so it can push the next is what makes so great reduction from the 4,000 feet, -even down to 36 feet in this illustration.

"Dr. Forel gave the thing a Swiss name, seiche, pronounced Sash, long a . . .

"The same thing was later studied by English engineers on lakes in

Scotland, and by Canadians; . . . Mr. Sabin in 1911 wrote about the oscillations in the canal just above the Poe lock in the St. Mary's River, resulting from abstracting water to fill the lock; and Col. Hodges, about 1915, wrote of the like phenomenon in Gatun Lake when filling the upper Gatun lock.

"Like results follow when water is slowly added for a considerable time, as would be seen after emptying a lock into the lower reach of a waterway, provided there is a bank or wall at the far end to return the pulsation.

"Mr. Sabin exhibits a hydrograph showing the long continued rises and falls above the lock which are nearly as even and smooth as saw teeth. By inspection of this graph I see the summits are 12-1/2 minutes apart. As the water is 25 feet deep the velocity is 8.02 times the square root of half of 25, or 28-1/2 feet per second. Multiplying this by the above 12-1/2 minutes or 750 seconds gives 21,375 feet, and half of this should be the distance from the Poe lock along the canal and its prolongation across the river. I do not know how well or badly this fits, for I have no Lake chart of that place. Maybe the depth of the river crossing differs from 25 feet, which would alter the result.

"Col. Hodges also shows a hydrograph indicating a periodic time of one hour and 31 minutes for Gatun Lake, and calculation like the above on approximate depth gives a distance which fits the length of the lake from the lock to the ends of either of the two horns. But the extreme irregularity of the shores in the two horns and the nearness of the shore between them causes confusion of pulsations returning at different times, which grows worse with each succeeding return as is seen on the graph

which is very rough as compared with the graph at the Poe lock.

"I have experimented much with a long rectangular trough of planed planks, using water all the way from 2 inches deep to 9 inches deep and never found observation of periodic time of surge created therein to be less than the calculated time, nor to exceed it by more than 1 per cent. There ought to be a small excess on account of friction.

"I could start the surge by either adding or subtracting water at one end, if not done too violently; or by giving the trough a push endwise on rollers, which is like adding water at one end and subtracting from the other at the same time, or by raising and lowering one end.

"The periodic time was halved when the depth of still water was quadrupled; and for each depth it was the same whether I started a violent surge or a gentle one, and so continued till the water came to rest, like a pendulum or a swing.

"But the greater the surge the greater the velocity of water attending it, which is the element troubling ships at a wharf in the slip. A lemon which just sinks and an orange which just floats showed the velocity and travel to and fro to be nearly as great at the bottom as at the top.

"An idea of the approximate maximum velocity, which is at the center of the length, may be gained by assuming that the difference between high water and low water at either end is a wedge with its head at the end of the trough and its sharp edge at the middle, and that between the times of high water at one end and high water at the other enough water to make the wedge must pass through the cross-section at the middle of the length which does not change much in height.

"Applying this idea to our harbor surge, we have a wedge about 4,500 feet long and say 2 feet wide at the head, which would be a rise of a foot and a fall of a foot, which is as much as anyone has reported. The volume of this wedge for each foot of width of a slip is 4,500 cubic feet, and this must pass a cross-section at the center one foot wide by 40 feet deep; or 112-1/2 cubic feet must pass through each square foot. But it has half of the figured 8 minutes and 20 seconds, or 250 seconds in which to do it, thus giving an average velocity of 45 hundredths of a foot per second. But the velocity is not uniform, being greater at the middle of the time and smaller at the ends, so that the maximum velocity may approach a foot per second or 2/3 of a mile an hour.

"At the quarter and the three-quarter points in the length of the trough, the velocities are about three-fourths as great as at the center, for about three-fourths of the volumes of the wedges are between those points, and the ends. I say <u>about</u> because I suspect the upper and lower faces of the wedge are not quite straight.

"Dr. Forel also found that the lake sometimes divided itself into halves, each oscillating as though a wall or partition were placed across the center; and that in such cases, which are called binodal seiches, the periodic time was 30-1/2 minutes.

"You will notice this 30-1/2 is not quite half of his 73, as one would expect, but maybe he was wrong a minute or two on one or the other, for with water rising and falling so slowly it is hard to see just at what moment it is highest. Besides a wind may have sprung up to accelerate or retard.

"In this binodal seiche ships would find the greatest horizontal

motion at the quarter and three-quarter points and only an up and down movement at the center as well as at the two ends.

"Observers have also detected trinodal seiches, and maybe others, whose periods of oscillations would need to be a third or other aliquot part of the uninodal seiche period, such as in your fiddle string.

"Thus a ship may feel the surge worst at one point in the length of a canal or slip when the oscillation is uninodal, and at another point when it is binodal or trinodal, but the velocity of the water, which alone troubles the ship, is only half as much as in the uninodal, provided the water rises only to the same height at the ends; for the wedges of water which are transferred to and fro are only half as long.

"I find also that, just as you have overtones accompanying the primary ones, my trough, when specially manipulated, may have a uninodal seiche accompanied by polynodal ones. Then the rolling egg or lemon on the bottom is much confused. It will sometimes halt and then go a little further before turning around. And the two seiches occasionally conspire to make it roll further and quicker than usual, especially when near the quarter or three-quarter point. In this way a ship may find water moving occasionally perhaps a half faster than at other times during the same experiences, so that possibly the maximum velocities in the slip may approach a mile an hour instead of the two-thirds mile figured a few moments ago.

"In my opinion, as I wrote before, what starts oscillations in the harbor is the arrival of one or more very long, though low, waves, which are the result of coalescence of many short and higher waves from a storm a thousand miles or more away. The rough sea of local storms do not do

it, for the surge is not found to be an accompaniment of rough water in the locality. Such seas do not push long enough. When a column of water humps its back to push the next it finds it has lost its backing through subsidence of the sea behind, and then retreats.

"Of course it is not impossible to have a surge at the time of a local storm, for there is a chance for the arrival at the same hour of a long wave from a far distant storm.

"Without the breakwater the long wave would come to shore and then depart never to return unless it should meet others at regular intervals which would enable it to oscillate between the point of meeting and the shore, which happening I think I have seen in an open harbor.

"Whether the long sea adds the water at the end of the basin to start a surge mostly by pushing it through the 40 per cent voids in the breakwater, or mostly by running it around the end of the breakwater, I am not yet very sure.

"The long sea will of course rise a little higher against the wall that stops it, and water only a foot higher outside than in, and lasting minutes instead of seconds, will run a lot of water through; for the flow is not limited to the voids in the upper foot, but extends all the way down, 40 to 50 feet . . .

"Some have advocated reducing the voids in the breakwater to lessen the inflow; but it must not be overlooked that if a surge is started by an inflow around the end of the breakwater it would not die down so fast if none of it could escape through the wall . . .

"If, after a surge is started in the present outer harbor, a wall were dropped to form an easterly side of the basin, we would not expect

the oscillations to stop immediately in consequence of the new wall, but to continue longer than before, because the escapeway for fractions of flows had been blocked.

"This is why some of us did not hope for relief to result from a breakwater proposed some years ago to be constructed from the shore south ward towards the light house, unless it went so far as to prevent entry of enough water to start the surge, in which case the gap would be too narrow for safety of navigation.

"Now suppose we make another harbor just to the east, of the same width and depth, so that oscillations in it, if any, would be like those in the present harbor. Then flows in each would prevent lateral escape of flows from the other as effectually as would a north and south wall between them, and the surge would be slower than now in tapering down.

"Of course the teaching of some, and the hope of others is that with the proposed walls built to create the second harbor there would be no surge even started in either; but I have been unable thus far to share in that hope.

"Of course all depends upon whether those long low waves from far distant storms find big enough holes through the breakwaters and the navigable gaps between them to push water enough through to start a surge . . .

"Now how much water needs to pass through? We wrote further back of a shifting wedge of water from 4,500 feet long and say 2 feet thick at the head. Only the upper half of the wedge had to be added to still water to start the uninodal or worst surge, and that half amounts to 2,250 cubic feet for each foot measured across the line of surge.

"And the 2,250 cubic feet would have a quarter of the periodic time

in which to enter, or a quarter of 8 minutes and 20 seconds, or 125 seconds, thus requiring entrance of only 18 cubic feet per second. As the entryway extends to depths of 45 feet or more at the breakwater only four tenths of a cubic foot per second needs to come through each foot of depth, or one square foot of section . . .

"The holes through the present breakwater are known to occupy four tenths of the mass, or a little more, and a velocity of one foot per second would furnish the four tenths cubic foot per second figured previously.

"How much higher must the water be on the outside of the breakwater than on the inside to produce that velocity? A difference in height of only a foot would cause a velocity of 8 feet per second were the holes only through a thin partition. But, instead of such holes we have long rough conduits averaging a hundred feet or more in length, full of crooks, enlargements and constrictions to consume most of the head; and to get even the roughest idea we must apply a formula for flow of water in pipes, and use in it a high coefficient of friction, say N = 0.035.

"Some idea of the cross-section of the pipes or conduits is had from knowing the smallest stones in the breakwater weigh 100 pounds, and there are but few of them, the great bulk of the enrockment being from 1,000 pounds to 10 tons. Since 0.6 of a cubic foot of the stone weighs 100 pounds, we may approximate by assuming this is 0.6 of a square foot in cross section and 1 foot long, and that it is accompanied by a conduit or void of 0.4 square feet by 1 foot, which just represents the 40 per cent voids.

"This would be equivalent to an 8-1/2 inch round conduit or 7.6 inch square one. But the real shape is still less favorable for flow,

hence we will use an equivalent triangle of 0.96 feet on the side.

"The hydraulic radius would be 0.21 feet, and the slope 1 foot in a hundred feet. Under these conditions, using 0.035 for N, the coefficient is 18, and the velocity is 18 times the square root of the product of 0.21 by 0.01, or 0.82 feet per second.

"Considering that much of the length of conduits is much larger, the rocks being mostly large, it appears that this 0.82 feet may be raised to the 1 foot per second figured a few minutes ago; and therefore that water averaging only 1 foot higher on the outside of the breakwater than on the inside can run enough water through the wall to start a uninodal surge provided the water will stay that high for about two minutes.

"I never timed those long low seas; but remembering my experience reading tide gages at the breakwater 22 years ago I have a strong impression they did hold up two minutes if not longer. A lesser velocity and flow through the breakwater could cause a surge of less violence than that assumed for this inquiry, - namely one that gives 2 feet of variation in height of water at the ends; and a flow through the breakwater for half the time could cause a binodal seiche.

"I used to think that marine growth, vegetable and animal, would choke the passages or voids, but after seeing rock of two old jetties removed, and breakwater rock after it had been disturbed by a steamer running into it, I have come to the opinion that such growth does not extend far into the dark. The growth may be prolific on and near the outside, but as only large rock was deposited on the slopes, the voids there are also large, so that stoppage by growth is hardly to be expected.

"It is seen, therefore, that the advice of some to use such sizes

of stone as will greatly reduce the voids is not to be laughed at, though it would be costly to follow. Even 20 per cent voids, making solids 80 per cent instead of 60 per cent, would increase the tonnage of stone 33 per cent.

"In some quarries the additional small stone could be furnished without increase of cost for quarrying and loading; for it is there, and has to be removed anyway; but in other quarries much of it would have to be made by harder shooting of large rock, and on that account, and the greater cost of loading small stuff, the unit price might be higher on all. In either event the hauling and unloading would cost 33 per cent more.

"The next wonder is whether the proposed gaps between the breakwaters would alone, without the aid of voids in the random mound breakwaters, admit enough water to start a surge.

"Hence let us assume the wedge widened to about 22,000 feet to cover the length of the harbor east and west exclusive of proposed developments or fills at the ends. Its volume is 4500 x 1/2 x 22,000, or say 50,000,000 cubic feet. The gaps, if each 2000 feet wide, by 50 feet deep, would give 200,000 square feet and the flow thru each square foot would need to be the quotient, or 250 cubic feet. And as the time is as before, 125 seconds, the velocity would need to be 2 feet per second.

"Can we expect enough head or height at the entrance or gaps to yield such flow? Rivers 2,000 feet wide and 50 feet deep without side friction to speak of would, by Bazin's Formula, flow 2 feet per second if the surface slope is as much as 1 foot in 39 miles, or about a quarter of an inch in the length of the wedge.

"We can see now that the narrowest entrances that anybody would sanction for navigation would admit enough water to start a surge whenever those long low waves from far distant storms come upon us.

"We could have seen it in a general way before, by thinking of the size of the harbor and its entrances in comparison with the size of Gatun Lake and the lock valves.

"It appears now that since the entrances alone will admit surge, there would be but little gain in reducing the voids in the breakwater; for in our case the magnitude of the surge depends on the height and duration of that long wave, and would be no higher were the breakwater removed.

"On the other hand partial stopping of the voids would reduce the escape of the surge and enable it to vibrate longer.

"The surge extends in a reduced degree into the inner harbor. I even found a little in the east basin channel near the Consolidated Lumber Company slip. Only the narrowness of the 550-foot channel past Reservation Point keeps it from being worse.

"I think that channel should not be widened till after the breakwater is built, and the assertion that there will then be no surge is proven by experience.

"I was not unfamiliar with the idea that, with an area behind a breakwater relatively large compared to the width of openings, the sea on entering would have so much room to fan out laterally that they would become moderated until they are harmless.

"But that does not apply at all to surge and its cause, which may not have come within the experiences of the writers quoted or copied, but

does apply only to the oscillatory short waves of local storms, which do not supply a material addition of water; but do soon become enfeebled through having to share their rotation with still waters which they encounter in the enclosure . . .

"I shall not bore you longer on surge itself, which is here to stay; but on what to do about it. My former letter indicated that to prevent breaking of lines we need only to prevent a ship acquiring momentum or energy through travel, by simply following that Pilots advice to keep it from ever starting.

"It takes no more force to hold that vessel still against an endwise flow of 1-1/2 feet per second, than to tow it a mile an hour in still water; and that requires a continuous pull of only a thousand pounds on a big ship, which can be borne by a hemp line smaller than your thumb.

"To tow side-on at the same rate would require much more pull; for in the former case little more than skin friction had to be overcome, amounting to a pound per hundred square feet of wetted surface if clean painted, and twice as much if foul; while in the latter case, the surface presented not being of fair form, the resistance is more like the pressure of a running stream against a plane, which on each square foot amounts to the square of the velocity in feet per second when in sea water.

"But even this is not excessive, amounting against a plane 500 feet by 30 feet to only 17 tons, which is the strength of a rope the size of your wrist.

"These bigger figures may make you suspect the vessels, side-on at the breakwater oil station, would be hard to hold. But the velocity figured there in my illustration was only eight-tenths of a foot over

40 per cent of the area, on about 3 tenths on the whole; which, being only 1/5 of the 1-1/2 feet used above, would push only one twenty-fifth as hard, and thus permit your smaller line, the size of your thumb, to withstand it.

"Then why don't folks follow that Pilot's advice and quit complaining about surge? Simply because they can't believe what they think is contrary to their own experiences.

"Every seafaring man knows a short tow line will break sooner than a long one, because the latter not only stretches farther, but, as a catenary being lifted from the water, it pulls much harder and for a longer time before becoming straight and snapping.

"And it is natural for them to believe without a doubt that long stretched lines are likewise best at a wharf in case of surge.

"I dwelt enough on the mechanics of the case in that other letter, and will now only scribble a less technical illustration.

"Suppose I play this pencil is a ship, and stretch it between two long rubber bands or cords pulled horizontally till the tension in each is, say 1 pound. Now I can start that pencil moving horizontally in the direction of either rubber cord as easily as if it were only suspended by a cord from high above; because, on the start, the elastic on one side helps me as much as the one on the other side resists.

"After moving, say an inch, I feel something opposing, because the elastic on one side now stretched an inch more resists harder, and the other stretched an inch less does not help me so much, and I feel the difference between the two pulls.

"Were the cords twice as long I would move the pencil twice as far

before feeling as much opposition. Were the cords only a quarter as long I could move the pencil only a quarter of an inch with the same effort. This is why the Pilot says "tie short and tight".

"If I replace one of the elastics by a steel rod which will not stretch perceptibly, nor bag down from its own weight; and leave the other elastic stretched with 1 pound tension as before, I cannot start the pencil away from the steel for the steel refuses to stretch; neither can I start it towards the steel, excepting by pushing with a force of more than 1 pound, because the elastic being under an initial tension of 1 pound, will not yield farther under any lesser force.

"I would therefore recommend tying a ship one way (no matter which) with a relatively short rod, or other tie that will not yield materially; and the other way with a hemp line stretched to an initial tension of 2 or 3 tons, either by a capstan on deck, or, wharf, or by hanging a weight on the line.

"The line need be only long enough to accommodate changing height of vessel due to seas, tides, and changing draft, without stretching beyond its strength, nor slackening till its remaining initial tension is less than the push of a surge.

"The line can be so short as not to occupy any wharf front beyond the length of the vessel, by tying it to another line or chain passing over a sheave on the wharf to a 2 or 3 ton counter weight below, and pulling on the line with a capstan or tackle till the weight is raised a few feet off the bottom.

"Thus there would be constant tension without any movement of the sheave except as the height of vessel changes, and there would be no

severe stress on any part.

"The stress in the line would never be more nor less than the weight of the suspended counterweight, excepting for friction at the sheave, and the stress on the rod would be the same, plus the push of the surge when it is away from the rod, and minus the push when it is the opposite way . . ."